SCHOOL OF CIVIL ENGINEERING

JOINT HIGHWAY RESEARCH PROJECT

JHRP-74-14

RTOR: WARRANTS AND BENEFITS

Ronald L. May

PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

74-14

Final Report

RTOR: WARRANTS AND BENEFITS

TO: J. F. McLaughlin, Director
Joint Highway Research Project

August 28, 1974

Project: C-36-17KK

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 8-4-37

Attached is a Final Report titled "RTOR: Warrants and Benefits". It has been authored by Ronald L. May, Graduate Assistant on our staff under the direction of Professor H. L. Michael.

This report contains the findings of an extensive review of the literature and an analysis of before and after studies of Right-Turn-on-Red (RTOR) as permitted with signs before July 1, 1974. Warrants from these studies and experience of others are then developed for use in the permissive RTOR without signs as effective in Indiana on July 1, 1974.

The warrants developed in this study were used by the ISHC and other governmental units in Indiana in implementing the Indiana 1974 RTOR regulation on July 1, 1974.

The report is presented to the Board for acceptance as fulfillment of the objectives of the study.

Respectively submitted,

Harold L. Michael

Harold L. Michael
Associate Director

HLM:jal

cc: W.L. Dolch
R.L. Eskew
G.D. Gibson
W.H. Goetz
M.J. Gutzwiller
G.K. Hallock
M.L. Hayes
C.W. Lovell
G.W. Marks
R.F. Marsh
R.D. Miles
G.T. Satterly
C.F. Scholer
M.B. Scott
H.R. J. Walsh
E.J. Yoder
S.R. Yoder

Final Report

RTOR: WARRANTS AND BENEFITS

by

Ronald L. May
Graduate Assistant in Research

Joint Highway Research Project
Project No.: C-36-17KK
File No.: 8-4-37

Prepared as Part of an Investigation
Conducted by
Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana State Highway Commission

Purdue University
West Lafayette, Indiana
August 28, 1974

ACKNOWLEDGMENTS

The author wishes to sincerely thank Professor Harold L. Michael for his guidance, comments, and constructive criticism throughout the course of this research, and in the preparation and review of this manuscript.

The City of Lafayette, Indiana, and the City of Indianapolis, Indiana, Department of Transportation, especially Lt. Robert Griffin and Mr. James Cox respectively, were essential to this research in providing the opportunity to examine intersections under their jurisdiction as well as providing supportive information. Thanks are extended to these organizations and people for their assistance with this research.

A very special thanks is extended to my wife, Susan, for her encouragement during the course of this study and her assistance in the preparation of this thesis. Also, a special thanks to my daughter, Jennifer, for her help in the completion of this study.

Appreciation is felt for the assistance provided by Dr. Roy C. Loutzenheiser for his help throughout the course of the study, and to my fellow students for their assistance with the collection of data and help throughout the remainder of the study.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

ABSTRACT

May, Ronald L., M.S.C.E., Purdue University, August, 1974 RTOR: Warrants and Benefits. Major Professor: Harold L. Michael.

This research was designed to examine intersection approaches utilizing the RTOR maneuver in an attempt to identify problems resulting from the maneuver and benefits that could be derived from it. Attempts were made to determine intersection characteristics which are common to these problems and benefits. The report includes a summary of the literature as of 1972 on the RTOR maneuver.

Data for this study were obtained from a study of intersections in Lafayette, Indiana and at intersections in Indianapolis, Indiana. Before studies were conducted at the Lafayette intersections, signs were then erected, and after a period of time additional studies were performed to observe the changes which occurred. The intersections in Indianapolis where the RTOR maneuver was already in use were examined to determine the effects of the RTOR maneuver.

The results of this study agree with the accident analysis of other studies. The total number of accidents at the study intersections did not increase. Neither, was there clear evidence that they decreased. It was also found that intersection approaches with a right-turn-only lane, lower speeds on the cross street, shorter cycle length, and only one lane of traffic on the cross street had a greater usage of RTOR opportunities. It was also found that no delays or hazards were encountered by pedestrians as a result of the RTOR maneuver. Delay reduction to right turning vehicles was found to exist, but

no means to predict the amount of delay reduction to be expected was developed. A graphical relationship between the number of opportunities for vehicles to turn into the cross traffic, and the volume of vehicles on the cross street was developed.

Finally, suggested warrants for prohibition of the RTOR maneuver were developed. These warrants are subdivided into three groups: 1) those required for reasons of safety; 2) those permissive for reasons of little benefit from the maneuver; and 3) those permissive because of adverse public reaction.

CHAPTER 1. INTRODUCTION

In 1937, authorities in California decided that motorists were wasting too much time waiting for red traffic signals. At that time they authorized a traffic maneuver known as right turn on red (RTOR). The original maneuver permitted a motorist to make a right turn while facing a red signal only when a sign was in place which stated that the driver could do so (restrictive RTOR). The driver was also required to stop first and yield to all pedestrians and vehicles legally within the intersection. After ten years of use with limited application and using a sign to permit the maneuver, some authorities believed that the maneuver would work at almost every traffic signal (permissive RTOR). In 1947, the state of California began permitting the RTOR maneuver at all locations unless a sign was in place which prohibited the driver from making the turn.

Until recently very little attention was given to the RTOR maneuver. Some of the states joined California and adopted the rule which permitted the RTOR maneuver unless a sign prohibited the turn. In the midwest and east some states adopted the rule which permitted the RTOR maneuver only at locations where a sign was in place allowing the driver to make the turn. Very few efforts were made to research the maneuver. In 1956 Ray (27) conducted research in California to measure the decrease in delay resulting from the RTOR maneuver, and the effect on the number of accidents. Similar studies were conducted on a smaller scale in various locations. Little effort was made to determine at what locations, if any, the RTOR maneuver would function smoothly and safely.

In the 1960 edition of the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD), the RTOR maneuver was highly discouraged. Since that time, members of the traffic engineering profession have debated whether or not the RTOR maneuver should even be permitted. Furthermore, those members of the profession in favor of the RTOR maneuver have not been able to agree on the method of signing. Nevertheless, the use of the RTOR maneuver continued to spread. In the 1971 edition of the MUTCD, the RTOR maneuver is permitted but only at locations where signs are in place allowing the driver to make the turn. In recent years, the RTOR maneuver has become widely accepted, but still in many places the maneuver is used only at ideal locations.

In August of 1972, the National Highway Traffic Safety Administration (NHTSA) proposed in the Federal Register that all states would be required to enact legislation to permit the RTOR maneuver at all locations unless a sign is in place prohibiting the turn (7). This proposal brought the issue of RTOR to the foreground. The Institute of Traffic Engineers passed a formal resolution which opposed the method by which NHTSA was attempting to establish the use of the RTOR maneuver. It recommended that the accepted method be that as promulgated through established means, through the National Committee procedure which existed for revisions in the Uniform Vehicle Code (UVC) and the MUTCD.

It would seem that the best approach in determining how the RTOR maneuver should be signed would be to establish a set of warrants for use of the maneuver. By having a technique for selecting intersection approaches where the RTOR maneuver will function smoothly and safely the number of RTOR approaches could be determined. By knowing this number of approaches a more logical signing choice could be made. After reviewing the literature, it was found that no generally accepted warrants for the use of RTOR have been developed.With this knowledge, this research project was begun to determine warrants and benefits associated with the RTOR maneuver.

The approach taken was to relate the effects of the RTOR maneuver to intersection characteristics which could be easily measured. It was agreed that accidents should be related to these characteristics since safety is very important. Other effects expected to be important were pedestrian delay and inconvenience, vehicle delays, driver irritation, opportunities for RTOR, acceptance of such opportunities, etc.

CHAPTER 2. REVIEW OF LITERATURE

Throughout the history of the RTOR maneuver no one has designed and performed a well organized study to examine the effects of the maneuver on the existing traffic. Of the studies that have been conducted, the majority dealt with collection of accident data for intersections where the maneuver was currently being used. The literature on RTOR can be easily divided into the areas of surveys of present use, accident studies, vehicle delay or travel time studies, gap availability, effects on capacity and level of service, and surveys of the warrants and intersection characteristics for using or not using the RTOR maneuver. Many of these reports dealt with more than one area. Some reports dealt with theoretical discussions while others were reports of actual field studies.

Present Use

The first area mentioned is present use of the RTOR maneuver. In 1972, thirty-two states permitted the RTOR maneuver in one form or another. These states are illustrated in Figure 1. Of these thirty-two states, nineteen allowed RTOR only when a sign was in place permitting the maneuver (21). Most of these states conformed with the UVC (21) by requiring the driver to stop first and yield to pedestrians or other vehicles legally using the intersection. However, Arkansas and Tennessee did not require the vehicle to stop or yield to pedestrians.

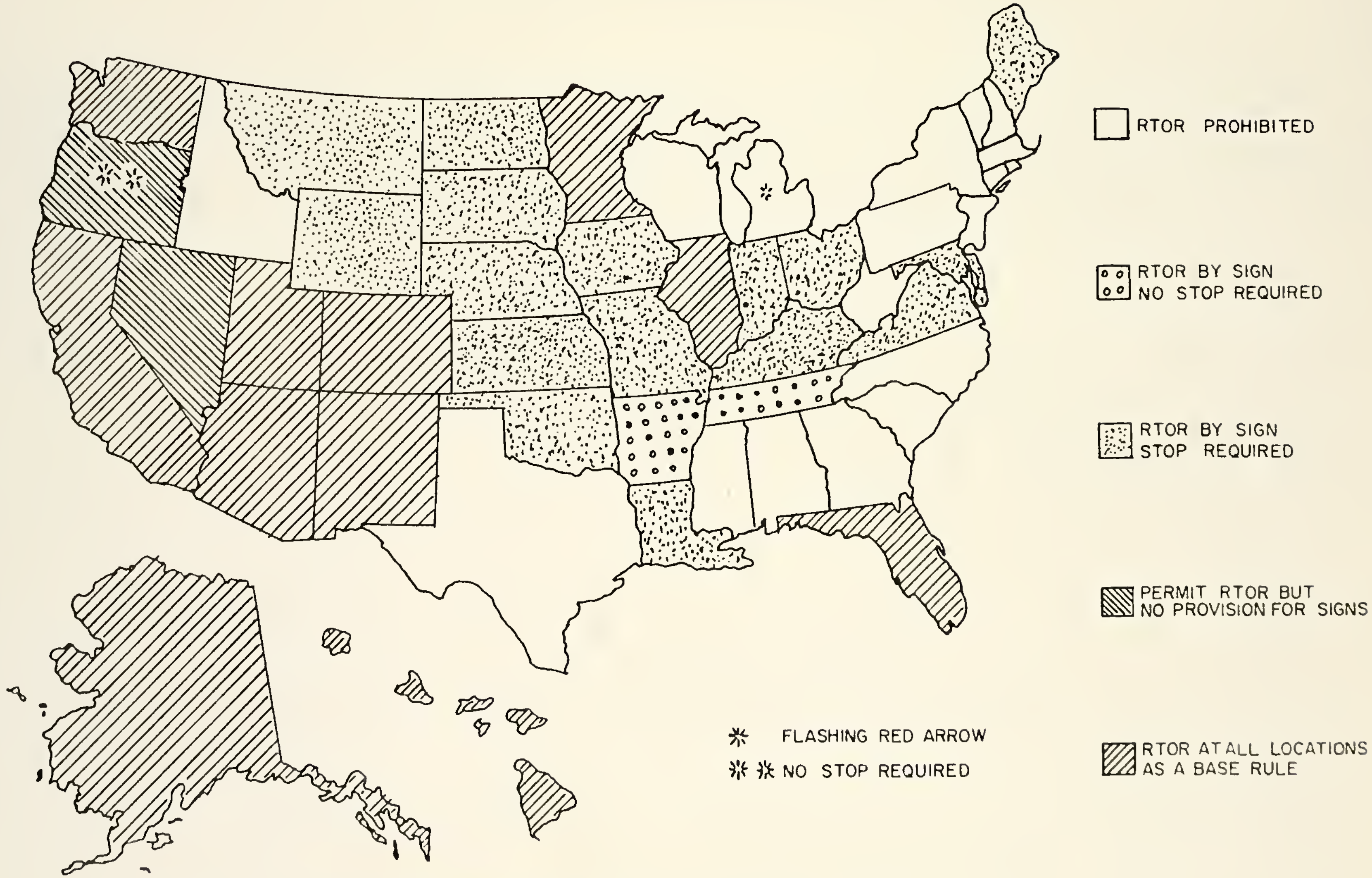

FIGURE 1. RIGHT-TURN-ON-RED USE IN 1972 (21)

Eleven of the remaining states permitted the RTOR maneuver at all signalized intersection approaches unless a sign was in place which prohibited the maneuver. These states also required the vehicle to stop and yield to pedestrians and other vehicles. The laws of the states of Nevada and Oregon made no provisions for signs of any kind, and Oregon did not require the vehicle to stop.

To add to the confusion, the city of Little Rock, Arkansas, violated their state law by permitting the RTOR maneuver by use of a green right turn arrow in place of a permissive sign. This green right-turn arrow does not mean that a vehicle can make a protected right turn as it means in other locations. In the state of Michigan, some cities used a flashing red right-turn arrow to signify a RTOR maneuver as the RTOR maneuver was not specifically provided in their state laws. In 1973 many states reconsidered their laws concerning the RTOR maneuver. As an example, Indiana passed legislation effective July 1, 1974 (35) to permit RTOR at any intersection in the state unless a sign restricts the maneuver. Illinois made a similar revision in their RTOR maneuver laws. It appears that the recent NHTSA proposal (7) will prompt other states to reconsider their laws.

Two interesting facts can be seen by looking at the present state laws governing the RTOR maneuver. First, the western states were first to use the RTOR maneuver and most strongly support its use while the eastern states most strongly oppose its use. It now appears that the permissive use of the RTOR maneuver is gradually spreading east across the country. The other item of interest is that locations using the permissive law permitted the RTOR maneuver at approximately ninety-six percent of their signalized intersections while locations using the restrictive law permitted the RTOR maneuver at only approximately two percent of the signalized intersections (17). These signalized intersections are probably obviously safe approaches so in reality the RTOR maneuver is seldom permitted except at such obviously safe locations when the restrictive law is used.

Accident Studies

The area given the most interest in the past has been accidents. Virtually every report on the RTOR maneuver has performed some accident analysis. One of the earlier studies conducted to examine the RTOR maneuver was performed by James Ray (27) in the San Francisco Bay area. In this study seventy-five intersections were studied. A total of 3,338 accidents were reported at these locations, but only twelve accidents involved RTOR vehicles. This data is tabulated in Table 1. These twelve accidents comprise only 0.3 of one percent of all accidents. Similarly, less than 0.8 of one percent of personal injury accidents were attributed to the RTOR maneuver. None of the RTOR accidents caused major personal injury. Further examination showed that eleven percent of the right turning accidents involved RTOR vehicles while the RTOR volume was eighteen percent of the total volume. This difference proved to be significant at a ninety-eight percent confidence level and led to the conclusion that the RTOR maneuver was at least no more dangerous than right rurn on green. The findings were the same for peak and nonpeak volumes.

RTOR pedestrian accidents consisted of twenty-two percent of the total right turn pedestrian accidents. Although this was greater than the eighteen percent volume of the RTOR maneuver the difference proved not to be significant at a ninety-eight percent confidence level. This led to the conclusion that the RTOR maneuver was no more dangerous to pedestrians than right turn on green. The general consensus of replies to a questionnaire used in the study was that RTOR accidents represented an insignificant proportion of the total accidents.

Table 1. Intersection Accidents as Reported by James Ray (27)

	Pedestrian volumes during peak hour crossing all approaches to intersection			Total Number of Accidents
	less than 50	50 to 500	more than 500	All Intersections
Number of Intersections Studied	24	35	16	75
All Reported Accidents	916	1763	659	3338
Injury Accidents Only	138	346	72	556
	Accidents Involving Right Turn on Green Vehicles			
Total	15	71	12	98
Injury Accidents Only	0	13	2	15
Pedestrian Accidents Only	0	12	2	14
	Accidents Involving Right Turn on Red Vehicles			
Total	2	8	2	12
Injury Accidents Only	0	3	1	4
Pedestrian Accidents Only	0	3*	1	4

*It is noted that in one case the pedestrian was crossing the street against a steady red indication, and the accident would be properly charged to a pedestrian violation rather than a vehicular violation of right of way.

In a summary of the RTOR maneuver practice in the western United States, Mathison (17) reported that the RTOR maneuver does not significantly contribute to accident experience. Only 0.77 of one percent of all accidents were attributed to the RTOR maneuver where the permissive law was used. However, where the restrictive law was used the accident experience varied greatly. It was felt that this variance may have resulted from inconsistencies in the signing techniques.

A study conducted by Howard in Jacksonville, Florida, examined 405 intersections (12). This report indicated that 0.74 of one percent of 1,756 accidents reported at these locations could be attributed to the RTOR maneuver. Only 0.11 of one percent were classified as vehicle-pedestrian accidents attributable to the RTOR maneuver. Traffic volumes were not available so exposures could not be calculated. At the time of the study, the state of Florida did not provide for the RTOR maneuver as a basic rule. This lack of uniformity could have actually raised the accident rate.

A report from a study performed in Colorado Springs, Colorado, indicated a high degree of success of the RTOR maneuver (32). After approximately one year of operation at eighteen approaches to ten intersections, no accidents had been reported which could be attributed to the RTOR maneuver. However, the RTOR maneuver was used only under "ideal" conditions. The following characteristics were required for RTOR installations:

1. A high percentage (25%) of the total volume of vehicular traffic in a given direction must turn right.
2. Delay to through-traffic was caused regularly by right-turn movements and/or right-turn vehicles typically were unable to clear on the green phase.

3. Very low pedestrian volumes existed and there was available a lane for the exclusive use of right-turning vehicles.
4. Streets were of sufficient width to accommodate the RTOR maneuver without undue or exceptional hazard, conflict or interference with other traffic.

In a similar situation in Santa Anna, California, Ray (28) reported that no accidents resulted from the RTOR maneuver. The city had thirty-six signalized intersections, but at thirteen of them the RTOR maneuver was prohibited. The study lasted for two years and four months. The study showed four pedestrians injured and one killed resulting from right-turning vehicle accidents. All of these accidents occurred while the vehicles were turning on the green.

In a study conducted in Los Angeles, California, Scott (30) reported that RTOR accidents amounted to less than 0.30 of one percent of all accidents at signalized intersections. However, RTOR vehicle-pedestrian accidents were slightly greater than two percent of the total vehicle-pedestrian accidents at all signalized intersections.

In a more recent study by the Minnesota Department of Highways, 197 intersections were examined in a before and after study (36). 1967 was used as the before period while 1968 was used as the after period. A problem occurred in that the 1967 accident data was incomplete. However, the following results were obtained. Accidents occurred at only thirty-two of the 197 intersections or sixteen percent. The before data showed that the thirty-two intersections had only nineteen percent of the total accidents. In the after study, the same thirty-two intersection accident total was twenty percent of the total accidents. The report indicates that if the incompleteness of the 1967 data was random, the RTOR maneuver accidents occurred, generally, at the more accident prone intersections. Another point made in this report was that the severity in accidents decreased after implementation of the RTOR maneuver. The accident totals are shown in Table 2.

Several interesting points were made about the nature of some accidents. Three accidents resulted when a right-turning vehicle lured a through vehicle into the intersection. Two other accidents resulted from the cross traffic traveling at an unsafe speed. The review of all the different accidents failed to reveal a common intersection characteristic. Appropriate statistical tests were made and the following conclusions were drawn:

1. Direction of approach did not influence the occurrence of RTOR accidents.
2. Although the difference was not significant, approaches involving moderate to heavy pedestrian volumes were relatively free of RTOR accidents. This would indicate driver caution and/or less RTOR maneuver use. The one RTOR accident involving a pedestrian occurred at 0645 hours at which time the pedestrian volume was extremely light.
3. Approaches with moderate to heavy cross street volumes had significantly more RTOR maneuver accidents than did approaches with low cross street volumes, probably due to higher exposure.
4. Although the difference was not significant, high volume right turn approaches had relatively more RTOR maneuver accidents, again probably due to increased exposure.

Table 2. Accident Experience as Reported by the Minnesota Highway Department (36)

Accident Totals

	Before	After
All Intersections:	1849	2000
32 R.T.O.R. Acc. Intersections:	368	402
Percent	19.9	20.1

Accident Severity

	Before		After		R.T.O.R.	
	Number	Percent	Number	Percent	Number	Percent
Prop. Damage	1212	65.6	1374	68.7	34	82.9
Pers. Injury	633	34.2	621	31.1	7	17.1
Fatality	4	0.2	5	0.2	0	0.0
Total	1849	100.0	2000	100.0	41	100.0

5. There were significantly more RTOR maneuver accidents at approaches with two lanes of traffic from the left than with one lane. This was probably due to heavier volumes on two lane roadways.
6. Although the difference was not significant, approaches with separate phase left turns and where the cross street also had a separate left turn phase had relatively fewer RTOR maneuver accidents than did approaches without separate phase left turns.
7. Approaches with usable right turn lanes had significantly fewer RTOR maneuver accidents than did those approaches without right turn lanes.
8. Although higher speed approaches had relatively fewer RTOR maneuver accidents, the difference was not significant and may have been due to a lower usage rate.
9. Four lane two-way roadway intersections with four lane two-way roadways had significantly more RTOR maneuver accidents, due probably to higher volume exposure.

The following was considered to be a typical approach where a RTOR maneuver accident occurred.

The intersection had:

1. less than 100 pedestrians crossing per day.
2. greater than 5,000 ADT on the cross street.
3. cross street traffic less than thirty-five mph.
4. more than 1,500 right turn vehicles per day.
5. two approach lanes with no exclusive right turn lane.
6. two lanes of traffic approaching from the left.
7. no left turn phase.
8. good sight distance.

Another study was conducted in Oklahoma City, Oklahoma at approximately the same time (34). The RTOR maneuver was used at all four approaches at seventy-nine intersections and at 225 approaches at other intersections. Again this study was a before and after study. The after study was conducted approximately one year after the signs were installed. The major portion of the accident investigation dealt with the seventy-nine intersections. Before the installation of the signs, 798 accidents were reported at these seventy-nine intersections. One year after the installation of the RTOR signs, 807 accidents were reported. This increase of nine accidents represents an increase of only 1.1 percent. During the same time period, the traffic volume grew from 1,797,883 intersection crossings to 1,908,426, an increase of 6.15 percent. Considering intersection crossings as a measure of exposure to accident probability, the accident rate was 4.7 percent less after the RTOR maneuver installations than before. This report seems to indicate that the RTOR maneuver does not increase the overall accident problems at these intersections.

In a survey conducted by the city of Wichita, Kansas, a wide range of opinions were reported (8). Of thirty-six cities reporting, eighteen cities felt that the RTOR maneuver created a pedestrian hazard and eighteen cities felt that it did not create a pedestrian hazard. On the question of vehicle hazards, only ten cities considered the RTOR maneuver to be a hazard to vehicles while twenty-three cities felt that it created no hazard. It should be understood that these responses were not necessarily based on studies, but on the opinions of the individual replying to the questionnaire.

Only one study reported an increase in accidents resulting from the RTOR maneuver. From a study in Fort Lauderdale, Florida, May (19) reported on accident experience at four intersections where the RTOR maneuver was permitted by sign. Total accidents increased by twenty-one percent at these intersections. Vehicle-vehicle accidents increased from zero to seven. Vehicle-pedestrian accidents increased from zero to five. A very interesting result was that rear-end accidents decreased thirty-one percent. Accidents involving RTOR vehicles accounted for thirty-eight percent of the total.

It is seen that a variety of studies have examined the effects of the RTOR maneuver on accidents. Almost every study showed the RTOR maneuver accidents to be insignificant. Many of the accident reports, when compared to traffic volumes, showed that accident rates were not increased with the implementation of the RTOR maneuver. In some reports the accident rate actually decreased. In other reports the RTOR maneuver was proven to be no more dangerous than right turn on green and in fact it may be safer.

Vehicle Delay and Travel Time Studies

Another area given some consideration is reduction of both delay and travel time resulting from the use of the RTOR maneuver. This basic reduction in delay will be for the time from when a vehicle can make a right turn while facing a red signal until the signal turns green. Drivers may be able to save additional time by being able to turn without waiting for a pedestrian queue to dissipate as they may have to do when they turn on green. Additional delay reduction will result from through or left turning vehicles moving closer to the intersection on the red phase. It may be also possible that the RTOR maneuver will reduce the travel time for a vehicle which can turn into the green band in a progressive signal system.

Again, Ray's study (27) in the San Francisco Bay area was one of the first to examine the delay and travel time reduction resulting from the RTOR maneuver. The delay reduction study was conducted at six different approaches throughout the study area. These intersections had · similar physical characteristics and were all controlled by two phased fixed time controllers. Traffic volumes and cycle lengths varied from intersection to intersection. Delay reduction was measured as the time from when a vehicle entered the intersection until the light turned green for the same approach. These measurements were made for both the off-peak and peak periods.

Attempts to establish a relationship between the time saved and the length of the red phase of the signal cycle gave a rank correlation coefficient of .943 for the off-peak period. For the peak period the rank correlation coefficient was only .600 for these two variables. This seems to indicate that as the volumes increase, additional variables influence the time savings. Figure 2 shows the plot of these two variables for peak and off-peak periods. The report stated that in all cases time was saved by the RTOR vehicles, and in no instances was delay to any other vehicle or pedestrians at the intersection increased. The conclusion was that the RTOR maneuver is justified in terms of reduced delay for right turning vehicles.

To further evaluate reduced delay, travel time studies were conducted over a course consisting of fourteen signalized intersections. The vehicle was driven straight through seven of the intersections and was turned right at seven of the intersections. The trips were run with the driver alternately turning only on the green signal and then on the red signal when it was safe to do so. The

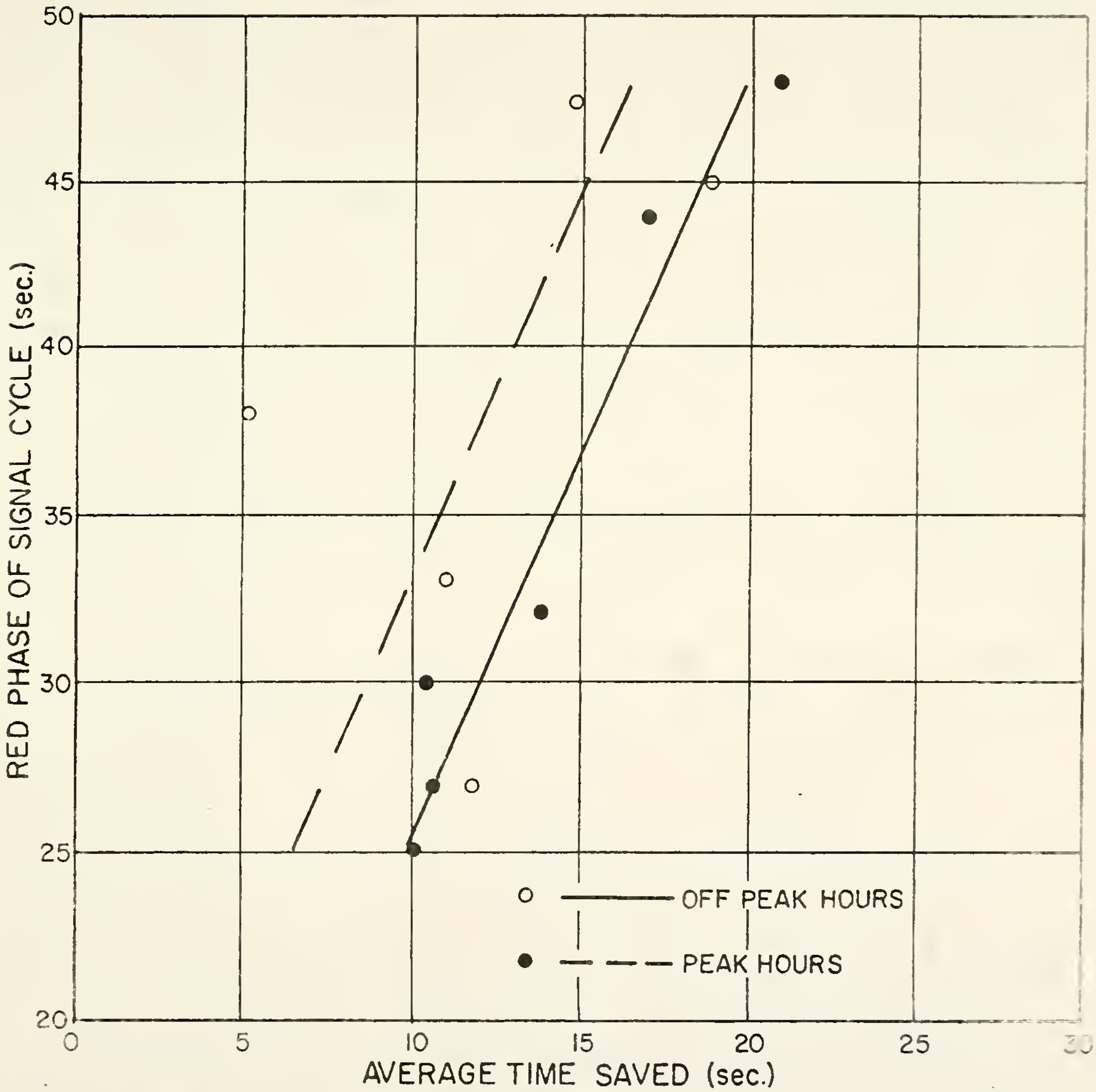

FIGURE 2. AVERAGE TIME SAVED PER RIGHT-TURN-ON-RED VEHICLE AS REPORTED BY JAMES RAY (27)

vehicle traveled at the speed of traffic or the posted speed limit. This process was conducted for both peak and off-peak periods.

For the off peak period it was found that the average travel time using the RTOR maneuver was .64 minutes less than for right-turn-on-green. This is about a seven percent savings. It should be noted that these trips were run through the CBD. The actual stopped time was reduced by sixty-eight percent at right turn intersections. The travel time delay reduction was greater for the peak period. Travel time was reduced 1.11 minutes or about ten percent. The difference in travel time is significant to the ninety-five percent confidence level. For both peak and off-peak periods the running times were not significantly reduced with the use of the RTOR maneuver. This study seems to demonstrate that the delay reduction occurs almost totally at right turn locations. Table 3 shows the results of the travel time study.

The study also made an attempt to measure the affect of pedestrians on vehicular delay. Pedestrian delay for right-turn-on-green vehicles results from pedestrians crossing directly to the right of the approach to the intersection. At no time, however, in the study was a vehicle turning right on green forced to wait through the next red phase. The thirty-two vehicles delayed by pedestrians while turning right during the green phase had an average pedestrian delay of .08 minute per vehicle. Some vehicles making a RTOR maneuver were also delayed by pedestrians crossing in front of them. The seventeen vehicles so delayed by pedestrians while performing a RTOR maneuver had an average pedestrian delay of .06 minutes per vehicle. This difference of .02 minutes per vehicle did not prove to be significant to the ninety-eight percent confidence level. Delays were measured during both the peak and off-peak periods.

Table 3. Results of Travel Time Study as Reported by James Ray (27)

Period of Day	Trips Making Right-Turn-On	Average Travel Time	Average Delay at Right Turn Signal	Total Delay at all Right Turn Signals	Average Running Time
OFF PEAK	Green	8.92	.25	1.00	6.80
	Red	8.28	.09	.37	6.66
	Difference	.64	.16	.63	.14
	Significant to 98% Level	Yes	Yes	--	No
PEAK	Green	10.97	.34	1.33	7.60
	Red	9.86	.21	.92	7.27
	Difference	1.11	.13	.41	.33
	Significant to 98% Level	No	Yes	--	No
	Significant to 95% Level	Yes	Yes	--	No

The study conducted by the Minnesota Highway Department (30) also examined the effects on delay resulting from the RTOR maneuver. Ten approaches at seven intersections were used in the delay study; five of the intersections had traffic actuated signals. A before and after technique was used. The delay was measured as the time from when a vehicle stopped until it completed its right turn. The study indicated that while some drivers apparently did not see the signs, an appreciable reduction in delay to right turning vehicles resulted from the use of the RTOR maneuver. The delay for RTOR vehicles was 11.44 seconds less on the average, which is approximately a forty-seven percent delay reduction. This reduction was approximately the same for peak and off peak periods as well as for fixed time and traffic actuated signals. Delays from the study are shown in Table 4.

William H. Van Gelder conducted a study in New York (38) similar to the Ray study. He used a rectangular course making right turns at three traffic signals. Van Gelder, like Ray, came to the conclusion that the RTOR maneuver has no effect on running time, but he indicated a substantial reduction in travel time over the prescribed course. An average delay reduction of fifteen seconds was reported for off-peak periods in this study, but no value was reported for peak periods.

Another study conducted in Colorado was reported by Scott (30). In his study he attempted to correlate delay with length of the red phase, RTOR volume, right turn volumes and volume of conflicting cross street traffic. Due primarily to his data sample size no correlation was found. Delay reduction varied from a low of 9.7 seconds to a high of 20.1 seconds. The average value reported was fourteen seconds.

Table 4. Observed Delay Reduction Resulting From RTOR as Reported by the Minnesota Highway Department (36)

Location	Direction	Time	Before (Sec.) Delay	Before # Veh. Delayed	After (Sec.) Delay	After # Veh. Delayed
T.H. 61 & T.H. 96	N.B.	P.M. Peak	3012.8	77	1395.1	53
		Off Peak	1204.6	70	562.4	73
	S.B.	P.M. Peak	855.8	33	466.6	36
		Off Peak	625.8	38	302.1	32
T.H. 61 & Parkway Drive	N.B.	A.M. Peak	121.2	7	39.4	7
		Off Peak	204.3	15	83.3	12
	S.B.	A.M. Peak	8705.2	335	2862.6	268
		Off Peak	1533.2	71	408.2	64
T.H. 212 & Jackson	W.B.	A.M. Peak	5857.4	244	4118.7	352
		Off Peak	6887.2	290	3482.9	268
I-94 & Snelling Avenue	N.B.	A.M. Peak	5769.7	374	1694.5	294

Table 4. (Continued)

Location	Direction	Time	Before (Sec.) Delay	Before # Veh. Delayed	After (Sec.) Delay	After # Veh. Delayed
T.H. 10 & T.H. 47	N.B.	P.M. Peak	3151.1	179	1289.9	146
		Off Peak	607.4	47	233.4	43
	S.B.	P.M. Peak	378.0	24	353.2	33
		Off Peak	534.1	31	217.7	34
T.H. 52 & T.H. 100	N.B. 52	P.M. Peak	7446.2	112	6449.0	195
		Off Peak	3522.5	106	2815.2	137
T.H. 212 & Payne	W.B.	Off Peak	1625.7	70	1006.0	78
	Totals		52041.6	2123	27780.2	2125

Mean Delay $\frac{52041.6}{2123} = 24.51$ Sec. $\frac{27780.2}{2125} = 13.07$

$\frac{24.51 - 13.07}{24.51}$ = 46.67% Reduction in Delay

In a report of experiences with the RTOR maneuver in Minnesota (36) it was indicated that in certain situations the cross traffic could be subjected to unnecessary delay. In a rural situation with an actuated signal on a minor cross street, a RTOR maneuver vehicle could register a call, but by the time the green signal is given to the side street the vehicle will already be gone as a result of the RTOR maneuver. If any vehicle approaches during this time on the main street, it will have to wait through the red phase although no vehicle is traveling from the side street. However, it should be noted that without the RTOR maneuver, the vehicle on the side street would have to wait for the green signal and the vehicle on the main street would have to wait for the vehicle on the side street. By looking at it in this manner, it is seen that the side street vehicle delay is reduced with the use of the RTOR maneuver and the main street delay is not changed. If a presence detector is used at the intersection on the side street the call may not be registered when a vehicle makes a RTOR, and the delay may be reduced for both streets.

Gap Availability

The availability of gaps in the cross traffic has been given very little attention in the past. A gap in the pedestrians crossing in front of the right turning vehicle must also be found, and it must coincide with the gap in traffic. No one has thoroughly examined the problem of pedestrian gaps.

In a study conducted by Betz, Bauman, and others at Arizona State University (2), it was determined that a gap of six seconds is the minimum acceptable gap for a right turn maneuver into a street with a speed limit of thirty-five miles per hour. At least eighty-five percent of all right turning vehicles rejected a gap of less than six seconds. Therefore, the gap acceptance for the RTOR maneuver is nearly always large enough so that the cross traffic is not forced to slow down. The study also found that there is no difference in the gap acceptance for right turning vehicles and vehicles turning left onto a one-way street. Both in-state and out-of-state drivers accepted about the same size gaps.

William G. Van Gelder (38) conducted a similar study in Seattle, Washington and in New York. In this study, he averaged rejected gaps and accepted gaps and determined an acceptable gap as being midway between the average rejected and average accepted gap. In Seattle, the average minimum acceptable gap was determined to be 4.25 seconds. In New York, the average minimum acceptable gap was determined to be 4.30 seconds. It was concluded that the minimum acceptable gap is approximately the same for both east and west coast drivers, and that their aggressiveness is approximately the same.

In their book Traffic Engineering, Matson, Smith and Hurd (18) reported that when a merging vehicle is stationary or moving at a slow speed prior to the act of merging, and accordingly a high relative different speed existed, the majority of drivers rejected gaps of less than 5.5 seconds but accepted gaps greater than six seconds. When gaps of less than five seconds were accepted, the rear vehicle forming the gap was usually retarded.

Solberg and Oppenlander reported on a study of lag and gap acceptance in Indiana (33). They examined four intersections to determine driver gap acceptance characteristics at stop controlled intersections. They came to the conclusion that the median acceptance times for right-turn movements was 7.36 seconds. They found that there was no significant difference between the median lag-acceptance and the median gap acceptance at these intersections. Also, they found that drivers in a small community required larger gaps than drivers in a large community.

No one has become very deeply concerned with the question of gaps in the pedestrian traffic. Only Ray has commented on this concept (27). In his study he found that sufficient gaps existed in both parallel and transverse pedestrian traffic to permit the desired right turning movement within the phase.

Capacity and Level of Service

The next area given consideration is capacity and level of service. No actual field studies have been conducted in this area; however, Van Gelder has developed a theoretical technique for determining the maximum RTOR maneuver volumes for given cross traffic volumes (38). It was determined that the first six vehicles in a queue have an average headway of less than four seconds, and the following vehicles have headways of two to three seconds. The RTOR maneuver must occur at the end of the queue since no acceptable gap will occur in the queue. The amount of time available for RTOR after the queue has cleared is dependent on volume, cycle length and cycle split. The time required for a queue to clear is calculated by the formula:

$$C_q = (2.1\ nR + H)\ [\sum_{o}^{x} (2.1\ n)^x]$$

$n = \frac{Q}{3600}$ = Average number of arrivals per second.

Q = Vehicles per hour.

R = Main street red in seconds.

G = Main street green in seconds.

C_q = Total time to clear queue.

H = 3.7 for nR=5 or more.

The time available for the RTOR maneuver is determined by subtracting the length of time to clear the queue from the total main-street green time. The gaps during the remaining time will approximate a Poisson distribution. The maximum number of RTOR maneuvers is then dependent on the number of gaps and the maximum right turns into these gaps. As the main street volume decreases, the time for the RTOR maneuver increases. Also, as the average number of main street arrivals decreases, the number of gaps decreases. However, these gaps will be capable of handling more right turning vehicles.

It was assumed by Van Gelder that since all vehicles are required to stop before making the right turn, the departure headway will be a constant. No field study has been performed to absolutely determine the headway, but a value of 4.3 seconds was assumed for purposes of simplifying calculations.

An additional equation was derived by Van Gelder to take into consideration the possibility of multiple entries into a single gap. The total capacity was calculated using the number of gaps and the average arrival rate of main street vehicles. This capacity was calculated from the probable number of gaps occurring which were of sufficient size to handle one vehicle, two vehicles, three vehicles, etc.

$$\text{Total Capacity} = \sum_{o}^{x} x\ N\ (e^{-xnt} - e^{-(x+1)nt}) = N\sum_{1}^{x} e^{-xnt}$$

$N = n(G-C_q)$ = Average arrivals in $(G-C_q)$ seconds

n = Main-street average arrival rate

t = 4.3 seconds

Using this formula with a ninety second cycle, sixty second main street and thirty second side street, Figure 3 is an example of the RTOR maneuver capacity. This Figure represents the maximum number of RTOR maneuvers possible when a continuous queue of right turning vehicles is present. The points plotted are actual observations. Of these points, seventy-two percent are within the capacity range established. The author speculated that the observations falling outside of the limits resulted from drivers not stopping before performing the maneuver which gave them a shorter headway than theorized and that the main street drivers had less than a 2.1 second headway at this high volume. The dashed vertical line represents the minimum possible number of RTOR maneuvers resulting from vehicles turning at the end of the queue. The line represents two vehicles per cycle.

From these calculations it appears that the RTOR maneuver volumes are a function of main street traffic, percent of red time for the side street, and the availability of right-turning vehicles.

Capacity is defined as "the maximum number of vehicles which has a reasonable expectation of passing over a given section of a lane or a roadway in one direction during a given time period under prevailing roadway and traffic conditions"(10). Capacity is, therefore, level of service E, and it is not logical to assume that more vhicles can be placed in the main street if it is operating at capacity or level of service F. The RTOR maneuver will not increase the capacity of the intersection, assuming the signal is properly timed. However, as the volume on the main street declines, the number of RTOR maneuvers can increase. As this number increases, the level of service for the side street and perhaps the entire intersection can be improved towards level of service A.

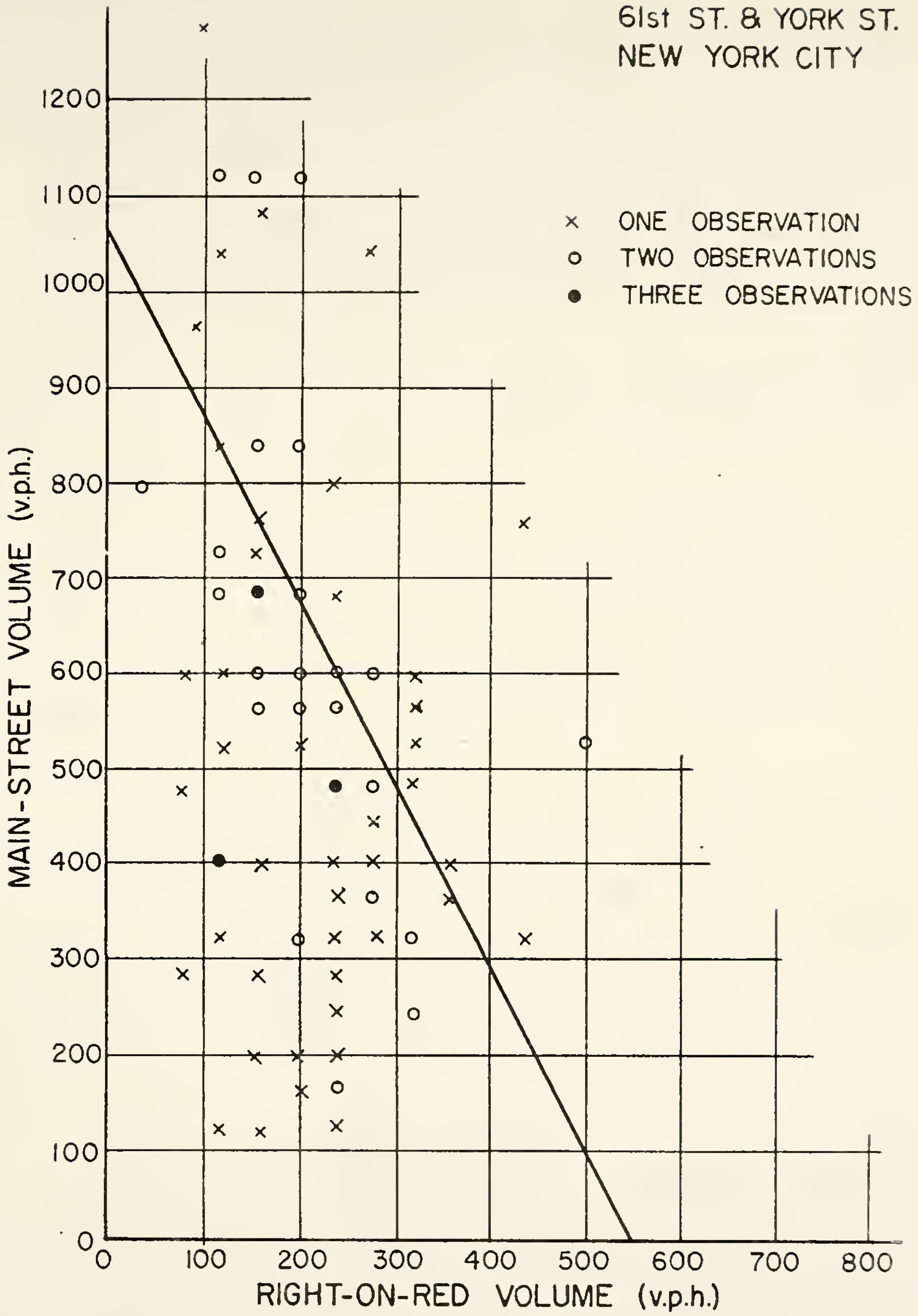

FIGURE 3. THEORETICAL AND OBSERVED R.T.O.R. VOLUMES AS REPORTED BY VAN GELDER (38)

The only other comment concerning the effects of the RTOR maneuver on volumes was by Smith. He said

> "Assuming the average red time to be 30 seconds and assuming that each vehicle comes to a full stop at the stop-bar, only four or five vehicles at best will make the turn on the red phase. This is scarcely enough to warrant the permissive (permission by rule) regulation" (32).

Using this example it can be shown that a substantial number of right-turning vehicles can move through the intersection on the red phase. If four or five vehicles can turn, an additional 240 or 300 vehicles could move through the intersection. As discussed earlier the capacity of the intersection would not be any larger, but the level of service of the approach allowing the maneuver could be improved with an increase of volume of this magnitude.

Ray (27) has demonstrated that the percentage of right-turning vehicles which can turn right on red remained constant for both peak and off-peak periods. He found this to be eighteen percent of the total right-turning vehicles. This volume ranged from two to thirty-seven percent of the total volume. The results of his study are shown in Table 5.

Warrants and Intersection Characteristics

While the RTOR maneuver has existed for over thirty years no individual or organization has developed a set of warrants for the use of the maneuver based on a good thorough investigation of the effects of the RTOR maneuver. Perhaps the most scientific investigation was conducted by the Minnesota Highway Department (36). This study was designed primarily to determine the relationship between accidents and the RTOR maneuver. As possible increased

Table 5. Traffic Volumes for Right-Turn-On-Red and Green as Reported by James Ray (27)

	Off Peak Hour	Peak Hour
Total Right-Turn-On Green Traffic Volume Observed	988	1054
Total Right-Turn-On-Red Traffic Volume Observed	219	233
Right-Turn-On-Red Traffic Volumes as a Percentage of Total Right Turn Traffic	18.1%	18.1%

accident experience constitutes one of the greatest objections to the RTOR maneuver, it would seem that using the maneuver where accident experience has been good would be one of the best warrants. While many of the findings were not statistically significant, they are a good guide for using or not using the maneuver. The findings are listed in the accident discussion section of this report.

When Smith (32) began his study on the RTOR maneuver in Colorado Springs, Colorado, he also established a set of warrants for the use of the maneuver. These warrants were contained in the study report and are also listed in the accident discussion section of this report. These warrants appear to be very arbitrary, and with the exception of the first warrant, they are very subjective.

Larry Erion (6) agreed with a study conducted in Wichita, Kansas (8) with regard to warrants for the RTOR maneuver. They both agreed that the following conditions should be met for use of the maneuver:

1. A large right turn volume should exist.
2. A low pedestrian volume should exist.
3. A low cross street vehicular speed should exist.
4. An exclusive right-turn lane should exist.

Wichita, Kansas added two more requirements for use of the maneuver:

1. A low cross street volume should exist.
2. An adequate sight distance should exist.

Similarly, Oklahoma City, Oklahoma (34) arbitrarily established warrants for the implementation of the RTOR maneuver at their study intersections. However, their warrants were all negative. The RTOR maneuver should not be permitted at:

1. CBD intersections where pedestrian activity is the greatest.
2. Intersections with restricted sight distance.

3. Intersections with critical signal off-sets.
4. Intersections with more than four approaches.
5. Intersections with left turn signals on the opposing approach requiring a merge with a RTOR vehicle into a single lane.
6. Intersections in school zones.

Mathison (17) reported on positive warrants for the use of the RTOR maneuver. The RTOR maneuver should be used where:

1. There is a separate right turn lane.
2. There are two lanes departing the intersection to the right.
3. There is adequate sight distance.
4. There is advance notice that the curb lane is a right-turn-only lane.

The Indiana State Highway Commission (14) has developed a more extensive list of criteria for not using the RTOR maneuver. The intersection characteristics which suggest the maneuver should not be permitted are:

1. CBD area with high pedestrian volumes.
2. Signals used by school children.
3. Approaches with only one approach lane.
4. Approaches with cross street volumes high enough to have no gaps available for safely performing the maneuver.
5. High speed rural intersections.
6. Intersections with heavy truck movements.
7. Multi-legged intersections where the turn can be made into or from more than one approach leg.
8. Intersections with restricted sight distance.
9. Intersections where other protected movements are permitted under separate arrow indications.

In the study conducted by Ray (27) questionnaires were sent to cities and states throughout the country. The results of this questionnaire indicated that warrants similar to the above were used throughout the United States. The following list of warrants for using the RTOR maneuver was compiled from the cities in the eastern part of the country:

1. Intersections with light pedestrian traffic.
2. Where intersection geometrics permit essentially a merging maneuver.
3. Where right turn volume is so heavy that it cannot be accommodated on the green phase.
4. Where the pedestrian volume is less than forty pedestrians per hour on the affected crosswalk.

The warrants for use of the RTOR maneuver from the western part of the country were compiled into the following list:

1. Prohibited in the CBD.
2. Right turning volume which is too large to accommodate during the green phase.
3. No serious pedestrian conflict.
4. Sufficient street space to have an only-right-turn lane.
5. No serious vehicle conflict.
6. Separate left turn signals for the cross street must be accompanied by right turn indications.

From this sampling of warrants, it is clear that almost all of them are arbitrary. The majority of the warrants are also very subjective. As a result of this subjectivity it would be very difficult, if not impossible to implement the RTOR maneuver in a uniform manner throughout the country with these warrants.

In 1972, the state of Minnesota began permitting the RTOR maneuver at all signalized intersections unless prohibited by a sign. A report in the North Central ITE Bulletin (16) gave some indication of the warrants used for prohibition of the maneuver. The Minnesota Highway Department felt there was no need for widespread prohibition of the maneuver. Their approach was to prohibit the maneuver only where, in their judgment, the maneuver would be extremely hazardous. The city of St. Paul, had installed no prohibitions at the time of the report. However, they were carefully watching multi-leg intersections. Such locations are where the first problems were anticipated.

The city of Minneapolis took a similar approach. They decided to prohibit the RTOR maneuver at established school crossings at signalized intersections, since they felt that elementary school children need all of the protection they could get. Hennepin County officials also felt that problems would be found at school crossings and in pedestrian areas with the RTOR maneuver. In general, traffic officials in the St. Paul - Minneapolis area have permitted the RTOR maneuver almost everywhere, and found little need to prohibit the maneuver anywhere by the time of the report.

This report on experiences in Minnesota (16) indicates that a different approach to use of the RTOR maneuver has been taken. No need has been found for arbitrary warrants for banning the RTOR maneuver. From the report, it can only be concluded that the widespread use of the permissive maneuver is working quite successfully.

Summary

In reviewing the literature it is obvious that attitudes about the RTOR maneuver are rapidly changing throughout the country. Many states which had completely prohibited the maneuver are now permitting it in some select locations. Other states which only allowed the RTOR maneuver at select locations are now or will soon be allowing it under a permissive law. The result will be much confusion for the driver as he travels from one state to another. Some local agencies even require special signs, green arrows, red arrows, etc., and in some situations these do not conform to the appropriate state law. The feelings about the RTOR maneuver are highly polarized in this country with the east coast being opposed to it and the west coast in favor of it.

The area given the most consideration in the literature has been accident analysis. Almost all of the reports have come to the conclusion that the RTOR maneuver accidents are a very small portion of the total accident experience. Some reports even indicate that the RTOR maneuver may be safer than right turn on green. It also appears that pedestrians may be safer with the RTOR maneuver than with right turn on green. Only one study by May (19) reported any bad accident experience with the maneuver.

Another area given a lot of consideration in the literature is delay reduction resulting from the RTOR maneuver. It was found in several studies that delay to right truning vehicles was reduced without increasing the delay for any other vehicles at the intersection. Also, it was found that travel time over a prescribed course which included a right turn was reduced. This delay reduction varied from 20.1 seconds to 9.7 seconds saved per right truning vehicle. It was also determined that the presence or number of pedestrians had no real effect on the amount of time saved with the use of the RTOR maneuver. Attempts were made to correlate the decreased delay with intersection characteristics. The R^2 values considered good enough to be reported ranged from .60 to .94.

An area of importance which has not been given much consideration to date is gap availability. Most of the literature dealing with gaps concerned itself with the size of gap which would be accepted for a RTOR maneuver. The size of reported acceptable gaps for right turning vehicles ranged from a minimum of 4.25 seconds to a median of 7.36 seconds. It was also found that adequate acceptable gaps generally exist in pedestrian traffic for right turning vehicles.

The only real examination of the effects of the RTOR maneuver on capacity was performed by Van Gelder (38). On a purely theoretical basis an equation was developed to determine the capacity increase resulting from the maneuver. The equation was based on the assumptions that the traffic must stop before making the right turn and that a continuous queue of right turning vehicles is present. When the equation was tested with field data, it was found that it provided a reasonable estimate of the maximum limit of RTOR maneuver volumes. It was found that the use of the RTOR maneuver did not increase the capacity of an intersection, but that it could improve the level of service of the approach when the cross street was not operating at capacity.

The final area reviewed was warrants and intersection characteristics. It appears that a variety of warrants have been used throughout the country. Almost all of these warrants are very arbitrary, and the application of them has been very subjective. In the Minnesota Highway Department study (36) intersection characteristics where accidents are likely to occur were identified. These characteristics could easily be used as warrants, and they are probably the most scientifically developed set available. Some cities in Minnesota (16), however, reported a different approach to the problem. They simply were only prohibiting the maneuver, under their new permissive law, at locations where specific problems arise. At the time of the report officials seemed to feel that the system was working quite well and very few locations had been found where it was necessary to prohibit the RTOR maneuver.

One warrant which generally is accepted as desirable for locations where the RTOR maneuver should not be permitted is concerned with sight distance. Inherent with sight distance and the RTOR maneuver is the fact that an acceptable gap for the maneuver must be visible if the movement is to be made safely. Some of the best work performed on gap acceptance has been done by Solberg and Oppenlander (33). They came to the conclusion that the median acceptable gap for a right turning vehicle is approximately 7.36 seconds. Using this value, Table 6 was derived which gives the sight distances required to allow a driver to be able to see far enough to select an acceptable gap. The sight distance from Table 6 should be available before the RTOR maneuver is permitted. This sight distance should be provided such that a driver has a clear line of sight for the distance when he has his vehicle properly stopped behind the stop-line. By providing this sight distance, the problem of vehicles encroaching on the crosswalk should be minimized.

Table 6. Recommended Sight Distance Requirements for RTOR

Speed in Mph	Minimum Sight Distance Sight Distance in Feet
20	217
25	271
30	325
35	379
40	434
45	488
50	542
55	596

CHAPTER 3. DESIGN OF THE STUDY

Techniques Used in the Study

In an attempt to establish warrants for the RTOR maneuver or to gain some understanding of the benefits that could result from the maneuver, it seemed appropriate to measure the changes in levels of various intersection characteristics. Initially it was decided that it would be important to know how the accident experience might change, how vehicle and pedestrian delay would be affected and how volume of vehicles at these intersection approaches might be changed.

With these ideas in mind, a study was designed to determine intersection characteristics which could be easily measured before the maneuver was implemented, and which would be good indicators of what changes would occur in the above characteristics. A before and after technique was used for measuring these changes. The before study was used to examine an approach leg of an intersection as if it were being considered for the implementation of the maneuver. A RTOR sign was then installed at this location. After a one month period the approach was again examined to measure any changes which had occurred. The one month time period was decided upon simply to work within the time restraints of the project. It would have been desirable to allow a longer time period, perhaps one year, before the after study.

The variables measured in the determination of the characteristics and benefits and the methods of obtaining their values are:

	Variable	Method
1.	Number of phases per signal cycle	Observation at location
2.	Length of red phase	Measured by stop watch at location
3.	Length of cycle	Measured by stop watch at location
4.	Nature of cross traffic flow upstream	Observation at location and from responsible implementing organization
5.	Speed of cross traffic upstream	Observation of posted speed limit and speed study
6.	Speed of approach traffic	Observation of posted speed limit and speed study
7.	Volume of cross traffic upstream	Pneumatic tube with recorder and manual count
8.	Volume of approach traffic	Pneumatic tube with recorder and manual count
9.	Volume of pedestrians crossing approach street	Manual count
10.	Number of through lanes of cross traffic upstream	Observation at location
11.	Percent of turning movements of cross traffic upstream	Manual Count
12.	Number of approach lanes	Observation at location
13.	Availability of right turn only lane	Observation at location
14.	Percent of right turn approach volume	Manual count
15.	Width of approach street	Measurement at location
16.	Number of cross traffic lanes downstream	Observation at location
17.	Volume of left turn on opposite approach on special phase	Manual count
18.	Sight distance	Measurement at location

19.	Pedestrian delay	Manual count of each type of delay occurrence
20.	Vehicle delay	Moving car technique
21.	Accident potential	Manual count of critical incident occurrences

The nature of the cross traffic flow upstream refers to the presence of a progressive signal system, local fixed time signal, stop sign, yield sign, or no control on the cross street upstream from the study approach. It was felt that the nature of this control would affect the arrival on the cross street which would control the availability of gaps for the right turning vehicle. The number of approach lanes was recorded as the number of lanes used by vehicles as opposed to the number of lanes marked at the location. This practice is in accordance with the recommendations of the Highway Capacity Manual (10) in the measurement of intersection capacity. It was felt that the width of the approach street might be important because it controls the length of time pedestrians could be in conflict with a vehicle turning right against the red signal. The number of cross traffic lanes downstream from the study approach was recorded because it determines the number of different maneuvers possible into the cross traffic.

All of the measurements were taken on a per hour basis except for the twenty-four hour counts. Each intersection was studied for four hours including both peak and non-peak periods during both the before and after studies. Attempts were made to conduct both the before and after study on the same day of the week and same hours of the day to help remove any variance due to normal changes in traffic patterns from hour to hour or day to day.

The dependent variables consisted of pedestrian delay, delay savings to vehicles, accident potential and volume changes. Pedestrian delay was divided into three types of delay: pedestrians prevented from leaving the curb, pedestrians forced to return to the curb, and pedestrians forced to wait in the middle of the street. Occurrences of each type of delay resulting from a right turning vehicle were recorded. The before study recorded pedestrian delay resulting from right turn on green vehicles. The after study recorded all pedestrian delay resulting from any right turning vehicle. The change in pedestrian delay was then used as the dependent variable.

A moving car technique was used to measure vehicle delay savings. A vehicle was driven through the intersection making a right turn from the study approach. Before entering the intersection a stop watch was started at a predetermined reference point. After traveling through the intersection, the stop watch was stopped at a second predetermined reference point. These reference points were selected in an arbitrary manner, but attempts were made to select points located where the vehicle had not started to slow down as it approached the intersection or was not still accelerating as it came away from the intersection. In the before study, all turns were made against a green signal. In the after study, the turns were made as soon as they could be made safely. Ten runs were made each hour in both the before and after studies. In an attempt to approach the intersection in a random fashion, a random period of delay was taken between each run. A number was selected from a random number table. The last two digits of this numberwere then used as a percentage. This percentage of the cycle length was used as the random delay between travel time measurements. The ten runs were averaged and the difference between the before and after averages was taken to be the average delay reduction resulting from the RTOR maneuver.

The measurement of the effect of the RTOR maneuver on accident experience proved to be more difficult. A technique has been developed by Perkins (24) and evaluated by Baker (1) which will correlate the number of accidents to the number of conflicts. Since it was anticipated that accidents would be very few or none, a conflict technique was used to measure accident potential. Perkins and Harris (24) and Hayward (9) both developed techniques for measuring these conflicts. Since every driver must evaluate many potential conflicts, it is suggested by Hayward (9) that an individual driver can by observation determine critical incidents. A critical incident method was used to measure accident potential for this study. The observer simply counted and recorded all defensive maneuvers by drivers, such as a swerve or severe hard braking, which he felt resulted from the driver attempting to avoid an accident. The count of these critical maneuvers, or accident potential, was recorded for both the before and after studies. The intent was to use the difference in these numbers, with the appropriate traffic volumes taken into consideration, as the relative change in accident expectation resulting from the RTOR maneuver.

An attempt was also made to measure driver irritation resulting from the RTOR maneuver. It was felt that some drivers would display irritation when they were not able to make a right turn, because the vehicle in front of them was in their way. This measurement was recorded as the number of occurrences of any display of irritation such as drivers sounding their horns.

Before the study was begun, it was decided that some measure of driver's acceptance was required. Therefore it was decided that the number of situations where a vehicle desiring to make a right-turn and having the opportunity to make it were counted and recorded. Also, the number of vehicles which then performed the RTOR maneuver were counted and recorded. These measurements permitted the calculation of the percent of drivers who made a RTOR maneuver when given the opportunity.

Selection of Lafayette Study Intersections

For the Lafayette study four intersections were selected. The first selected was the intersection of Main Street and Sixth Street. This intersection was selected primarily because it is near the CBD and has relatively high pedestrian volumes. As a result of one-way street operation only two approaches were used.

The intersection of Ninth Street and Ferry Street was also selected because it was near the CBD. During the peak period this intersection had high volumes of vehicles. It was also expected that some pedestrians would be present at this intersection during the study period. All four approaches were used for the study.

Another intersection used in the study was Eighteenth Street and Union Street. This intersection had a right-turn-only lane. High vehicular volumes were anticipated here and this intersection is larger than any other in the Lafayette study. Since Union Street is also a one-way street, only two approaches were used.

The final intersection used in the study was Kossuth Street and Sixteenth Street. This intersection was selected because of its extremely low volumes. The traffic signal located there is probably not warranted. All four approaches were used.

The twelve approaches at these four intersections were studied for four one hour periods before and after erection of RTOR signs. The four hour periods were either from 7:00 A.M. to 11:00 A.M. or 2:00 P.M. to 6:00 P.M.

Beginning in May, 1973, the data were taken for the before study. On June 27, 1973 the RTOR signs were installed. After the signs had been installed for a minimum of a one month period and the motoring public had an opportunity to become accustomed to the maneuver at these locations, the data were taken for the after study.

Study of Existing RTOR Intersections

Another study of RTOR vehicle effects was made at intersections in Indianapolis. In late 1968 the City of Indianapolis, Indiana installed signs permitting the RTOR maneuver at a large variety of intersections under their jurisdiction. Since the maneuver had been permitted there for approximately five years and the motoring public had a good opportunity to become accustomed to it, these intersections were used in this study. No specific number of intersections was dictated for the study. Instead it was decided that as many intersection approaches as possible with a variety of characteristics should be examined.

Again, the intersections were selected so as to possess certain characteristics. One of the first considerations was the volumes on the street crossing the approach permitting the RTOR maneuver. Attempts were made to utilize some intersections near the CBD. These intersections had relatively high volumes during peak periods and as a result of being near the CBD, they also had large pedestrian volumes. An attempt was also made to select intersections in outlying areas which would have a wide range of volumes during the study period. The approach intersections to be studied were limited to the ones with only one or two through lanes from the left on the cross street. Observation of approaches with more than two through lanes from the left on the cross street showed that drivers only required that the first two lanes be free of vehicles before they would attempt a RTOR maneuver.

At each of the selected approaches, a four hour study was made of pedestrian delay, accident potential, RTOR maneuver opportunities and use, and driver irritation. The data collected as measures of each of these factors were the same as for the before and after study in Lafayette except for pedestrian delay and accident potential. Rather than using the change in pedestrian delay occurrences by type, it became necessary (because of no before study) to simply use the number of pedestrian delay occurrences by type resulting from a RTOR maneuver. Rather than using the change in accident potential occurrences, it likewise became necessary to use the number of accident potential occurrences resulting from a RTOR maneuver.

It was further decided that a new dependent variable should be considered in the study, the number of gaps in the cross traffic as they could be an important consideration for the RTOR maneuver. The number of gaps was measured by observation at each site. One gap was counted and recorded each time a gap large enough for a vehicle to make a right turn was observed. If the gap was large enough for more than one vehicle to turn, the number of vehicles which could have turned into the gap in the cross traffic was recorded.

A need for a further refinement in the data collection technique was found during the Lafayette study. It was found that a one hour sample period tended to obscure affects of peak flows. Often a peak flow condition would not exist for a full hour or it would not coincide with a clock hour which was the basis for the data collection. In an attempt to record data better during periods of peak flow, data were collected and recorded for one half hour periods. In retrospect, it may have been better if time periods had been fifteen or twenty minutes so as to better measure the effects of higher volumes.

The data collection for the Indianapolis study was begun in September, 1973. Thirty-six intersection approaches were examined for the study. These intersection approaches are listed in Appendix A. The data collection was completed in October, 1973.

While the intersection characteristics data were being collected, the information required for the accident analysis was also sought. Attempts were made to get the accident records from 1967 through 1970 for each of the selected RTOR maneuver intersections. However, the accident records for this time period were in storage. The only records readily available for this period were collision diagrams, and the only ones available were for intersections with high accident experience. Furthermore, it was impossible to determine from the diagrams which, if any, accidents resulted from a RTOR maneuver.

As a result of this situation, it was decided to perform an accident analysis on any RTOR maneuver intersection in Indianapolis where collision diagrams or accident totals were available for the before period (1967-68) and the after period (1969-70). Accident totals were also found for some RTOR maneuver intersections for the years 1968 (before) and 1969 (after). These data were also used. The list of RTOR intersections used for the accident analysis portion of this study is found in Appendix B. It should be noted that not every approach to each RTOR maneuver intersection included in this analysis permitted the RTOR maneuver.

CHAPTER 4. ANALYSIS

The discussion of the analysis will be approached in a manner similar to the review of literature. The analysis will be divided into several different items to be examined. The first area to be examined will be the accident analysis. In a similar manner, the number of drivers and percentage of drivers using the RTOR maneuver, the delay change, displays of driver irritation, pedestrian delay change, and the availability of gaps will be examined.

Accidents

The accident analysis can again be broken into three categories. The first category to be examined is the change in accident potential resulting from the implementation of the RTOR maneuver. The second category to be examined is the accident records from fifty-four intersections in Indianapolis, Indiana. The third and final category is the accident records from the four intersections used in the Lafayette study.

Accident Potential Change

As described in the Design of the Study, an attempt was made to measure accident potential. In the Lafayette study, the accident potential was measured for the entire intersection during both before and after. The value being measured was the change in the accident potential. In the Indianapolis study only accident potential directly connected to a RTOR maneuver was recorded.

The data on accident potential recorded in the before and after studies in Lafayette were so meager as to be of little value in evaluating safety of the RTOR maneuver. During the before study, only three critical incidents were recorded at the four intersections during the sixteen hours of study. In the after study only one critical incident was recorded for the same time and it did not involve a RTOR maneuver.

In the Indianapolis study where only critical incidents involving RTOR maneuver vehicles were recorded, only four such incidents in seventy-six hours were noted.

The values obtained were too few to permit a meaningful analysis except for the observation that the RTOR maneuver did not appear to cause any important changes in safety at the intersections studied.

Existing RTOR Maneuver Intersection Accident Study (Indianapolis)

The accident information at RTOR maneuver intersections in Indianapolis was broken down into the categories of personal injury, property damage, and pedestrians. To suppliment the list of accident numbers compiled in this manner, the total number of accidents was available for some other intersections. The list of intersections and the number of accidents by type or total are shown in Appendix B.

To analyze this data, the number of accidents before the signs were erected were compared to the number of accidents after the installation of the RTOR maneuver signs. It is desirable to utilize the "Student's" t-test in an attempt to determine if more accidents occurred after the signs were installed than before the signs were installed. To properly utilize the "Student's" t-test the data being tested must have a normal distribution. The Shapiro-Wilk test was employed to test the normality of the data. Table 7 shows the personal injury accidents, both before and after, for thirteen intersections which had such data available for

Table 7. Personal Injury Accident Data 1967-1970

	Number of Accidents												
Before	12	0	2	3	5	1	7	7	8	6	8	23	11
After	18	5	6	6	7	3	9	7	6	3	5	20	5
Decrease	-6	-5	-4	-3	-2	-2	-2	0	2	3	3	3	6

$\bar{D} = 0.54$ $t = 0.54$ $W = 0.947$

$S_{\bar{D}} = 1.02$ $t_{.95,12} = 1.78$ $W_{.05,13} = 0.866$

$\bar{D}$ = Average decrease in the number of accidents

$S_{\bar{D}}$ = Standard deviation of the mean of the decrease

t = Computed t value for the "Student's" t-test

$t_{.95,12}$ = Critical t value for the "Student's" t-test

W = Computed W value for Shapiro-Wilk test

$W_{.05,13}$ = Critical W value for the Shapiro-Wilk test

Note: Accidents are reported by intersection for a two year period before (1967-68) and after (1969-70).

both two years before and two years after. The critical W value for thirteen observations and alpha equal to .05 is $W_{.05,13} = 0.866$. Since the computed W value is W = 0.947, the hypothesis of normality can not be rejected, and it is concluded that the data has a normal distribution. The t value for "Student's" t-test for twelve degrees of freedom and alpha equal to .05, is not in the critical region, and the null hypothesis that there is no difference in the accident experience before and after the installation of the RTOR maneuver sign could not be rejected. It should be noted, however, that there were more accidents in the two year after period than in the two year before period.

Table 8 shows the property damage accident experience for the same four year period. Again a Shapiro-Wilk test was used and the hypothesis of normality could not be rejected. Also a "Student's" t-test was performed on the data, and again the null hypothesis that there was no difference in the property damage accident experience before and after the installation of the RTOR maneuver signs could not be rejected. It should be noted here that there were less property damage accidents in the two year after period than in the two year before period.

The same procedure was followed to examine the pedestrian accident experience. Table 9 shows the number of pedestrian accidents at these same intersections. The Shapiro-Wilk test was employed again. However, the hypothesis of normality was rejected. Several transformations, square root, logarithm, inverse, etc., were utilized, but all of them failed to normalize the data. As a result of the nature of the data no statistical tests can be performed on the data. It can only be noted that there were four more pedestrian accidents in the after period than in the before period.

Since accident information for the total number of accidents was available for seven additional intersections for the appropriate four year period, a Shapiro-Wilk test and a "Student's" t-test were performed on the total data.

Table 8. Property Damage Accident Data 1967-1970

	Number of Accidents												
Before	29	9	22	16	7	11	1	16	27	7	19	30	22
After	43	16	28	20	8	10	2	14	22	2	11	22	3
Decrease	-14	-7	-6	-4	-1	-1	-1	2	5	5	8	8	19

$\bar{D} = 1.15$

$S_{\bar{D}} = 2.08$

$t = 0.56$

$t_{.95,12} = 1.78$

$W = 0.972$

$W_{.05,13} = 0.866$

Note: Accidents are reported by intersection for a two year period before (1967-68) and after (1969-70).

Table 9. Pedestrian Accident Data 1967-1970

	Number of Accidents												
Before	0	0	0	0	0	0	0	0	0	1	0	0	1
After	0	0	0	0	0	0	0	0	0	1	1	1	3
Decrease	0	0	0	0	0	0	0	0	0	0	-1	-1	-2

$\bar{D} = -0.31$

$S_{\bar{D}} = 0.175$

$W = 0.568$

$W_{.05,13} = 0.866$

Note: Accidents are reported by intersection for a two year period before (1967-68) and after (1969-70).

The data for the intersections are tabulated in Table 10. The hypothesis of normality could not be rejected, and it was concluded that the data is normally distrubuted. The null hypothesis that there was no difference in the total number of accidents during the two year period after the RTOR maneuver signs were installed and the two year period before the signs were installed could not be rejected since the computed t value is not in the critical region. However, if an alpha value of .10 is used, the computed t value falls in the critical region, and the null hypothesis could be rejected. It is then probable that the total number of accidents decreased after the RTOR maneuver signs were installed.

An additional number of intersections had accident information available for a one year period before the RTOR maneuver signs were installed and a one year period after the signs were installed. A total of thirty-three intersections had accident information by type available and a total of fifty-four intersections had total number of accidents available. The intersections used in the previous analysis are included in these data groups. The first group of data are the personal injury accidents. These data are tabulated in Table 11. Since there are more than thirty intersections in these groups a "Student's" t-test could be properly used to test the null hypothesis that there was no difference in the number of personal injury accidents in the one year period before the RTOR maneuver signs were installed than in the one year period after the signs were installed. The procedure used here is the same as the one followed with the four year accident data. Since the computed t value was not in the critical region, the null hypothesis could not be rejected. It should be noted, however, that ten more personal injury accidents occurred at these intersections during the after period.

The data tabulated in Table 12 are the property damage accident information. The null hypothesis that

Table 10. Total Accident Data 1967-1970

	Number of Accidents																			
Before	34	9	52	16	2	24	15	23	9	13	18	17	24	23	37	34	27	28	33	51
After	46	21	63	20	5	27	16	24	8	11	15	13	18	15	29	26	16	17	8	17
Decrease	-12	-12	-11	-4	-3	-3	-1	-1	-1	2	3	4	6	8	8	8	11	11	25	34

$\bar{D} = 3.70$

$S_{\bar{D}} = 2.53$

$t = 1.46$

$t_{.95,19} = 1.73$

$W = 0.910$

$W_{.05,20} = 0.905$

Note: Accidents are reported by intersection for a two year period before (1967-68) and after (1969-70).

Table 11. Personal Injury Accident Data 1968-1969

Number of Accidents

Before	0	5	3	2	10	0	0	7	0	3	5	12	1	3	3	0	3
After	4	1	3	3	10	2	1	2	1	6	4	10	3	0	5	1	6
Decrease	-4	4	0	-1	0	-2	-1	5	-1	-3	1	2	-2	3	-2	-1	-3
Before	4	0	3	8	1	1	7	2	2	1	1	3	0	4	0		
After	3	0	1	5	1	1	2	2	3	7	3	5	0	4	2		
Decrease	1	1	2	3	0	0	5	0	-1	-6	-2	-2	0	0	-2		

$\bar{D} = .30$

$S_{\bar{D}} = .434$

$t = .698$

$t_{.95,32} = 1.694$

Note: Accidents are reported by intersections for a one year period before (1968) and after (1969)

Table 12. Property Damage Accident Data 1968-1969

	Number of Accidents																
Before	8	4	18	16	11	4	5	5	0	4	11	11	2	5	5	2	5
After	7	5	12	10	17	6	5	1	0	10	8	25	0	2	2	3	6
Decrease	1	-1	6	6	-6	-2	0	4	0	-6	3	-14	2	3	3	-1	-1
Before	2	3	3	7	0	1	7	8	5	1	13	6	5	2	2	9	
After	3	1	3	15	0	1	5	5	5	7	7	5	4	4	2	2	
Decrease	-1	2	0	-8	0	0	2	3	0	-6	6	1	1	-2	0	7	

$\bar{D} = .42$

$S_{\bar{D}} = .75$

$t = .563$

$t_{.95,32} = 1.694$

Note: Accidents are reported by intersections for a one year period before (1968) and after (1969) there was no difference in the number of property damage accidents during the one year period before the RTOR maneuver signs were installed, and the one year period after the signs were installed could be rejected since the computed t value did not fall in the critical region. Here it is seen that fourteen less accidents occurred during the one year period after the signs were installed.

An analysis of the pedestrian accidents was also conducted. The data for this analysis are tabluated in Table 13. Since the computed t value does not fall in the critical region, the null hypothesis that there was no difference in the number of pedestrian accidents during the one year period before the RTOR maneuver signs were installed and during the one year period after the signs were installed could not be rejected. The number of pedestrian accidents, however, was increased by two in the after period.

The final analysis performed on accident data was for the total accidents for fifty-four intersections during the two year period. The data for this analysis are tabulated in Table 14. The computed t value falls in the critical region and the null hypothesis that there was no difference in the total number of accidents in the one year period before the RTOR maneuver signs were installed and the one year period after the signs were installed could be rejected. Since there were twenty-four fewer accidents during the one year after period it can be concluded that there were less accidents after the RTOR maneuver signs were installed.

In summary, it is seen that the installation of RTOR maneuver signs seems to have had very little affect on the accident experience at RTOR maneuver intersections in Indianapolis. Results were similar for both the two and four year studies. For personal injury accident examinations the number of personal injury accidents increased after the signs were installed, but the increase was not significant at an alpha level of .05. In a similar

Table 13. Pedestrian Accident Data 1968-1969

Number of Accidents

Before	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
After	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0
Decrease	0	0	0	1	0	0	0	0	0	-1	-1	0	0	-1	0	0	0	0
Before	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0			
After	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0			
Decrease	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0			

$\overline{D} = .06$

$S_{\overline{D}} = .074$

$t = .810$

$t_{.95,32} = 1.694$

Note: Accidents reported by intersections for a one year period before (1968) and after (1969)

Table 14. Total Accident Data 1968-1969

Number of Accidents

Before	8	9	21	18	21	4	5	12	0	7	16	23	3	8	8	2	8	6	
After	11	6	15	13	27	8	6	3	1	17	13	35	3	3	7	4	12	6	
Decrease	-3	3	6	5	-6	-4	-1	9	-1	-10	3	-12	0	5	1	-2	-4	0	
Before	3	6	15	1	2	14	10	7	2	18	7	8	2	6	9	7	11	29	
After	1	4	20	1	2	7	7	8	15	14	8	9	4	6	4	6	7	8	
Decrease	2	2	-5	0	0	7	3	-1	-13	4	-1	-1	-2	0	5	1	4	21	
Before	6	7	3	5	5	7	6	6	6	6	9	11	5	5	2	6	1	7	3
After	7	5	6	1	7	5	6	8	13	5	2	5	6	2	2	7	1	8	4
Decrease	-1	2	-3	4	-2	02	0	-2	-7	1	7	6	-1	3	0	-1	0	-1	±

$\bar{D} = .41$

$S_{\bar{D}} = .229$

$t = 1.78$

$t_{.95,53} = 1.674$

Note: Accidents reported by intersections for a one year period before (1968) and after (1969) manner, the number of property damage accidents decreased, but it also, was not a significant difference. It appears that the number of pedestrian accidents increased after the signs were installed. However, this increase was not proven to be significant. Finally, the total number of accidents decreased for both the two year and the four year studies. For the two year study, this difference was significant at the $\alpha = .05$ level. Also, the four year total accident study showed a significant difference at the $\alpha = .10$ level. The results of these tests are summarized in Table 15.

Lafayette Study Intersection Accident Experience

After the RTOR maneuver signs had been in place in Lafayette for six months, some accident information was available. This information has been collected and is discussed here. Due to the limited number of intersections and the limited amount of accident experience, no absolute conclusions can be drawn.

The intersection of Sixth and Main Streets had the most accidents of the four intersections used in the study. During the six month period before the RTOR maneuver signs were installed six accidents were reported. Two of these accidents involved vehicles striking illegally parked vehicles while making right turns. Three other accidents resulted from vehicles being struck in the rear. The remaining accident involved a vehicle making a right turn. After the signs were installed only one accident was reported in six months. This accident involved a vehicle being struck in the rear while making a right turn on a green signal.

Table 15. "Student's" t-Test Results for Accident Data

Accident Type	Computed t	Critical $t_{\alpha} = .95$	Significant
Four Year Statistics			
Personal Injury	0.527	1.782	No
Property Damage	0.556	1.782	No
Pedestrian	**		
Total	1.462	1.729	No*
Two Year Statistics			
Personal Injury	0.683	1.694	No
Property Damage	0.663	1.694	No
Pedestrian	0.180	1.694	No
Total	1.775	1.675	Yes

*Significant for $\alpha = .10$
**Insignificant data available for statistical test

Note: Rejection of null hypothesis leads to the conclusion of less accidents during the after period.

At the intersection of Ninth and Ferry Streets six accidents were reported for the one year period. Two of these accidents occurred during the six month period before the RTOR maneuver signs were installed. One accident involved a vehicle being struck in the rear, and the other accident involved a right turning vehicle. In the six month period after the signs were installed four accidents were reported. Again one accident involved a vehicle being struck in the rear. Two accidents involved right turning vehicles. The fourth accident was a vehicle striking a power pole. None of these vehicles involved were RTOR maneuver vehicles.

The intersection of Eighteenth and Union Streets had only two right angle accidents reported, one before the RTOR maneuver signs were installed and one after the signs were installed. The intersection of Sixteenth and Kossuth Streets had no accidents reported during the one year period.

The RTOR maneuver does not appear to have any effect on the accident experience. No sudden increase in the accident experience was observed at the study intersections. A total of nine accidents were reported at the four intersections in the six month period before the signs were installed, but only six accidents were reported during the six month period following the installation of the signs. It appears that the accidents are simlar in type and number before and after the signs were installed.

RTOP Usage

During both the Lafayette and Indianapolis studies, the number of opportunities to perform a RTOR maneuver and the number of times these opportunities were utilized were recorded. These data were then used to compute the percent of the opportunities which were used. An opportunity to perform a RTOR maneuver was considered to exist when the first vehicle in the right curb lane desired to turn right while facing a red traffic signal and an appropriate gap was available. It was not considered to be a RTOR maneuver opportunity unless the vehicle eventually turned right, either on the green or red signal indication. The number of opportunities utilized were the opportunities when a vehicle performed the right turn before the signal changed to green.

Initially, attempts were made to develop equations which would predict the value of these variables based on easily measured intersection characteristics. These attempts at employing regression analyses proved to be unsuccessful in that no acceptable R^2 values were developed.

The number of RTOR maneuver opportunities ranged from a low of no opportunities to a high of 174 opportunities per hour. The average number of opportunities was 16.00 per hour. The number of RTOR maneuvers performed ranged from a low on no maneuvers to a high of 173 maneuvers per hour. The average number of maneuvers performed was 8.10 maneuvers per hour. The percentage of the RTOR maneuver opportunities which were utilized ranged from a low of zero percent to a high of one hundred percent. The average percent utilized was fifty-four percent.

Since it did not prove feasible to develop equations to predict the usage of the RTOR maneuver, it became appropriate to attempt to determine which intersection characteristics could be associated with a higher degree of usage. To do this, analysis of variance was employed. All of the null hypotheses tested here were that there was no difference in the means of the two groups tested. In all of these tests v_1 is equal to one and an alpha value of .05 is used unless specified otherwise.

The data were grouped for each test by dividing the data into two groups based on the intersection characteristics being tested. A Bartlett-Box F test was used to test for homogeneity of variance with an α value of $\alpha = .05$ for each test.

Only two intersection characteristics were found to have any reasonable effect on the number of RTOR maneuvers.

The data were divided into two groups, one with intersections having a right-turn-only lane and the other with intersections not having right-turn-only lanes. The group with the exclusive turning lane had an average number of RTOR maneuver occurrences of 12.96 and the group without had an average number of occurrences of 6.42. The computed F value for this division of the data was F = 14.34. The critical value for $\alpha = .05$ and $v_2 = 294$ is F = 3.95. The null hypothesis can be rejected, and it can be concluded that intersection approaches with right-turn-only lanes had more RTOR occurrences than the intersection approaches without the exclusive lane.

The data were divided into groups with two phases per cycle and more than two phases per cycle. The average number of RTOR maneuver occurrences was 7.77 for the group with two phases per cycle and 12.70 for the group with more than two phases per cycle. The computed F value for this grouping was 2.59. If an alpha value of .11 is used the critical F value for $v_2 = 294$ degrees of freedom is 2.55. At this alpha level, the null hypothesis can be rejected. It is therefore probable that the number of RTOR maneuver occurrences was greater at intersection approaches with more than two phases per cycle than at intersection approaches with two phases per cycle.

As a result of nonhomogeneity of variance, other groupings for other intersection characteristics could not be tested in this manner. It was noted that one intersection characteristic, intersection approaches with a right-turn-only lane, had an average number of RTOR maneuver occurrences of 30.72 and intersection approaches without right-turn-only lanes had an average number of RTOR maneuver opportunities of only 10.86.

Percent usage of opportunities at RTOR maneuver intersections was also analyzed in the same manner as for occurrences. Four intersection characteristics were found to be significant factors in the percent utilized.

When the intersection approaches were divided into a group with the cross traffic speed greater than thirty-five miles per hour and a group with the cross traffic speed less than thirty-four miles per hour, the approaches with slower cross traffic had an average percentage of use of fifty-six percent and the approaches with faster cross traffic had an average percentage of use of forty-five percent. The computed F value for this grouping of data was $F = 5.64$, and the critical F value for $\alpha = .05$ and $v_2 = 294$ is $F = 3.95$. The null hypothesis can be rejected, and it can be concluded that a larger percentage of drivers who were given the opportunity to perform a RTOR maneuver did so when the cross traffic speed was slower than when it was higher.

By dividing the intersection characteristics into a group with cycle lengths greater than sixty-nine seconds and cycle lengths less than sixty-nine seconds, the first group had an average percentage of use of thirty-seven percent and the second group had an average percentage of use of fifty-four percent. The computed F value for this grouping was $F = 13.38$. The critical value for $\alpha = .05$ and $v_2 = 294$ degrees of freedom is $F = 3.95$. The null hypothesis can be rejected here, and it can be concluded that more drivers utilized the RTOR maneuver when the opportunity presented itself when the cycle length was shorter than when the cycle length was longer. This finding was surprising and may have resulted because of other intersection characteristics associated with short and long cycles. Certainly further study of this indicated conclusion is desirable.

When the data were divided into a group with one through lane of cross traffic and a group with two or more through lanes of cross traffic, the first group had an average percentage use of fifty-nine percent and the second group has an average percentage of use of fifty-one percent the computed F value for this grouping of data was F = 4.81. The critical value for $\alpha = .05$ and $v_2 = 294$ degrees of freedom was F = 2.95. The null hypothesis can be rejected, and it can be concluded that a higher percentage of drivers utilized a RTOR maneuver opportunity when there was only one through lane on the cross street than when there was more than one through lane. This too may be surprising and should be further researched.

By dividing the data into a group with sight distance less than 285 feet and a group with sight distance greater than 285 feet, it is found that the first group has an average percentage of use of forty-five percent and the second group has an average percentage of use of fifty-seven percent. The computed F value for this grouping of the data is F = 6.63. The critical F value for $\alpha = .05$ and $v_2 = 294$ degrees of freedom is F = 3.95. Again the null hypothesis can be rejected, and it can be concluded that more did utilize RTOR maneuver opportunity when the sight distance was greater than when the sight distance was shorter.

The data were grouped by other intersection characteristics, but none of the groupings proved to have a significant difference at the $\alpha = .05$ level. However, when the data are divided into groups with pedestrian signals and without pedestrian signals the average percentage of usage was sixty percent for the first group and fifty-one percent for the second grcup. The computed F value for this grouping of data is 3.49. The critical F value for α level of .10 and v_2 of 294 degrees of freedom is 2.74. The null hypothesis can now be rejected at this alpha level, and it can be concluded that it is probable that a larger percentage of drivers utilized RTOR maneuver opportunities at intersection approaches with pedestrian signals.

The problem of nonhomogeneity of variance prevented the analysis of RTOR maneuver occurrences by means of analysis of variance. However, observations were made concerning the number of RTOR maneuver occurrences. At intersection approaches with only one through lane of cross traffic the average number of RTOR maneuver opportunities was 10.46 and the intersection approaches with more than one through lane of cross traffic had an average number of RTOR maneuver occurrences of 6.54. When the data were divided into a group of intersection approaches with the speed on the approach less than thirty-four miles per hour the average number of RTOR maneuver occurrences was 7.22 and a group of intersection approahces with the speed on the approach greater than thirty-five miles per hour the average number of RTOR maneuver occurrences was 20.15.

Delay Reduction

A portion of the Lafayette study was designed to examine the reduction in vehicle delay at signalized intersections resulting from the RTOR maneuver. More specifically, the delay reduction analysis was for right turning vehicles. An average travel time making a right-turn from the study approach was determined for both the before and after study. The delay reduction was taken to be the difference between the average travel time before and the average travel time after.

The reduced delay for the twelve approaches at the four intersections used in the Lafayette study ranged in value from a low of minus .20 of one second (an increase in delay of .20 of one second), to a high of 15.23 seconds. The reduced delay data are displayed in Table 16. These differences were examined by means of the "Student's" t-test to determine if the differences were significant. To properly use the "Student's" t-test to test the equality of two groups of data it is necessary to determine that the variances are equal. The ratio of the before and after variances, S_2^1/S_2^2, were compared to the critical F value for the appropriate degrees of freedom. The hypothesis that the before and after variances were equal was rejected for four intersection approaches; Union and Eignteenth Streets northbound, Ferry Street and Ninth Street westbound, Kossuth Street and Sixteenth Street northbound, and Kossuth Street and Sixteenth Street eastbound.

The square root transformation was successfully used on the data for Union Street and Eighteenth Street northbound. The mean value of the transformed before data is 5.36 seconds and of the transformed after data is 4.20 seconds. The variance of the transformed before data is 1.228 and of the transformed after data is 0.743. The ratio of the before and after variances is 1.653 which is less than the critical F value of $F_{.95,39,39} = 1.705$, and the null hypothesis of equal variances can not be rejected. It was concluded that the transformed data have equal variances. The values presented here were used to calculate the t value in Table 16.

Again a square root transformation was succesfully used on the data for Kossuth Street and Sixteenth Street eastbound. The mean value of the transformed defore data is 4.83 seconds and of the transformed after data is 4.21 seconds. The variance of the transformed before data is 0.229 and, the variance of the transformed after data is 0.207. The ratio of the before and after variances is 1.098 which is less than the critical F value of $F_{.95,39,31} = 1.785$, and the null hypothesis of equal variances can not be rejected. It was concluded that the transformed data have equal variances. The values presented here were used to calculate the t value shown in Table 16.

Several transformations (square root, logarithm, inverse, etc.) were attempted on the data for the westbound approaches to the intersections of Ferry Street and Ninth Street and Kossuth Street with Sixteenth Street, but they failed to give equal variances for the transformed before and after data. Therefore it was appropriate to use an estimate of the t value for unequal variances for these two approaches. The computed t estimates are shown in Table 16.

It is seen that only the westbound approach to the intersection of Kossuth and Sixteenth Streets and the southbound approach to intersection of Ferry and Ninth Streets did not have a significant difference in the before and after period. There are not any intersection characteristics common to these two approaches and uncommon to the other approaches. The westbound approach to the intersection of Kossuth and Sixteenth Streets had a very short red time and another signal one block upstream from the intersection.

Table 16 indicates that the delay reduction for the northbound approach to the intersection of Kossuth and Sixteenth Streets and the eastbound approach to the intersection of Ferry and Ninth Streets were not statistically significant at an alpha level of .05, but the delay reductions at these two approaches were significant at an alpha level of .10 Only one intersection approach, westbound approach at the intersection of Kossuth and Sixteenth Streets, had an increase in the travel time in the after period. However, this increase was only 0.20 seconds and was not statistically significant.

Of the differences that were found to be significant, the smallest difference was 0.98 seconds, and the largest was 15.23 seconds. These differences are displayed in Table 16.

Table 16. Delay Reduction Data

Intersection	Approach	Before $\bar{X}_1$*	Before S_1^2	Before n_1	After $\bar{X}_2$*	After S_2^2	After n_2
Union St. & 18th St.	Eastbound	34.89	278.22	40	29.86	216.87	40
	Northbound	29.90	195.66	40	18.33	73.56	40
Main St. & 6th St.	Westbound	43.95	215.50	40	31.59	166.04	40
	Southbound	33.79	100.93	40	26.21	105.32	40
Ferry St. & 9th St.	Westbound	21.29	21.29	30	17.00	73.45	30
	Northbound	21.70	42.62	30	17.19	67.97	30
	Eastbound	38.04	114.49	30	25.34	126.36	30
	Southbound	21.02	151.08	30	19.18	134.66	30
Kossuth St. & 18th St.	Westbound	17.47	34.13	40	17.67	51.35	32
	Northbound	21.88	219.74	40	18.35	35.72	32
	Eastbound	18.97	34.37	40	17.99	16.63	32
	Southbound	18.97	78.87	40	18.72	47.93	32

$\bar{X}_1$= Average travel time in before study

$\bar{X}_2$= Average travel time in after study

n_1= Sample size in before study

n_2= Sample size in after study

S_1^2= Variance of the before study data

S_2^2= Variance of the after study data

* All average travel times in seconds

Table 16. (Continued)

Intersection	Approach	S_1^2/S_2^2	Critical $F_{\alpha=.05}$	Significant	Transformation
Union St. & 18th St.	Eastbound	1.283	1.705	No	
	Northbound	2.660	1.705	Yes	$X' = \sqrt{X}$
Main St. & 6th St.	Westbound	1.298	1.705	No	
	Southbound	1.043	1.705	No	
Ferry St. & 9th St.	Westbound	3.474	1.864	Yes	*
	Northbound	1.595	1.864	No	
	Eastbound	1.104	1.864	No	
	Southbound	1.122	1.864	No	
Kossuth St. & 16th St.	Westbound	1.505	1.785	No	
	Northbound	6.152	1.785	Yes	*
	Eastbound	2.067	1.785	Yes	$X' = \sqrt{X}$
	Southbound	1.646	1.785	No	

* No transformation was found which produced equality of variance.

Note: Rejection of hypothesis leads to the conclusion of unequal variances.

Table 16. (Continued)

Intersection	Approach	$\overline{X}_1-\overline{X}_2$	Computed t	Degrees of Freedom	Significant α = .05	Significant α = .10
Union St. & 18th St.	Eastbound	5.03	1.480	78	No	Yes
	Northbound	11.57	1.665***	78	Yes	Yes
Main St. & 6th St.	Westbound	12.36	3.952	78	Yes	Yes
	Southbound	7.58	3.338	78	Yes	Yes
Ferry St. & 9th St.	Westbound	4.29	2.415*	45**	Yes	Yes
	Northbound	4.51	2.349	58	Yes	Yes
	Eastbound	17.70	4.482	58	Yes	Yes
	Southbound	1.84	0.596	58	No	No
Kossuth St. & 16th St.	Westbound	-0.20	0.131	70	No	No
	Northbound	3.53	1.373*	54**	No	Yes
	Eastbound	0.98	6.894***	70	Yes	Yes
	Southbound	4.52	2.436	70	Yes	Yes

$$t = \frac{(\bar{X}_1 - \bar{X}_2)}{S_p\sqrt{(1/n_1) + (1/n_2)}}$$

$$S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}$$

$$*t = \frac{(\bar{X}_1 - \bar{X}_2)}{\sqrt{(S_1^2/n_1) + (S_2^2/n_2)}}$$

$$**\text{Degrees of Freedom} = \frac{(S_1^2/n_1 + S_2^2/n_2)^2}{\frac{(S_1^2/n_1)^2}{(n_1 - 1)} + \frac{(S_2^2/n_2)^2}{(n_2 - 1)}}$$

***t value computed from transformed data as discussed in text.

Driver Irritation

In both the Lafayette and Indianapolis studies, driver irritation incidents were recorded. These irritation occurrences were any occurrence which seemed to indicate that a driver desired the vehicle in front of him to perform the RTOR maneuver. In the study, as expected, the only form of driver irritation observed was a driver sounding his horn.

Only one intersection approach in the Lafayette study had any driver irritation displayed. This intersection approach was eastbound Union Street at Eighteenth Street. During the four hour after period, eight incidents of driver irritation were observed. It should be noted that the after study was conducted only one month after the signs were installed, and it is very probable that many drivers were not yet familiar with the maneuver. Also, while the approach does not have an exclusive right-turn lane, the right curb lane has a high right-turning volume and someone not familiar with the intersection could perceive this lane to be an exclusive right-turn lane.

During the Indianapolis study, six intersection approaches experienced driver irritation occurrences. Only the eastbound approach at the intersection of Alabama and North Streets had more than one occurrence of driver irritation, and it had two in a four hour period. The eastbound approaches to the intersections of Bluff Road and Troy Avenue and Michigan and Alabama Streets; the northbound approaches to the intersections of Sherman Avenue and Twenty-first Street and Alabama and North Streets; and the southbound approach to the intersection of Emerson Avenue and Sixteenth Street had one dirver irritation occurrence each. These intersections have very few common characteristics. Some are located near the CBD and some are located in outlying residential areas. These intersections have relatively high volumes on the study approaches. However, it appears that these driver irritation occurrences were very random in nature.

The most notable finding observed is the response to driver irritation occurrences. During the Lafayette study only one driver performed a RTOR maneuver when the driver behind him sounded his horn. It appeared that the other drivers either did not see the sign or they felt unsafe in performing the maneuver.

A similar situation was observed during the Indianapolis study. Only once each, at the eastbound approaches to the intersection of Alabama and North Streets and Bluff Road and Troy Avenue, was a response to a driver irritation occurrence seen. Again, it appears that a driver will not yield to pressure and perform the RTOR maneuver. If he does not perform the maneuver at his earliest convenience, he will probably not perform the maneuver at all.

Pedestrian Delay

As was mentioned earlier, the problem of pedestrian delay resulting from a RTOR maneuver was of interest to this study. In the Lafayette study, pedestrian delay resulting from the RTOR maneuver was considered to be the difference in the pedestrian delay by type observed during the before and after study. For the Indianapolis study, the RTOR maneuver pedestrian delay was taken to be the number of pedestrains delayed by vehicles performing a RTOR maneuver and was recorded by type.

Very few occurrences of pedestrian delays were observed. At the intersection of Main and Sixth Streets in Lafayette two pedestrians were forced to wait on the curb by a right turning vehicle during one hour of the before study. Three other pedestrians were forced to wait on the curb by a vehicle turning right on a green signal during a different hour of the after study at the same intersection. In each instance the pedestrians were together in one group. At the intersection of Kossuth and Sixteenth Streets in Lafayette one pedestrian was forced to wait in the middle of the street by a right turning vehicle. No other pedestrian delays were observed in the Lafayette study.

Of the pedestrian delays observed, it appeared that the pedestrians hesitated and, therefore, induced the vehicle to proceed with the turn. No pedestrian delays were observed during either the Lafayette study or the Indianapolis study resulting from a RTOR maneuver.

Pedestrian volumes in the study ranged from zero to approximately 130 pedestrians per hour with the majority of the samples having approximately seventy or less pedestrians per hour. It appears that the RTOR maneuver has no adverse effects on pedestrian travel up to the pedestrian volumes observed.

Of the intersection approaches studied in Indianapolis thirteen had pedestrian walk-wait signals. Some concern has been expressed about intersections with pedestrian signals and the RTOR maneuver. However, at the intersection approaches with pedestrian signals in this study no situations were found which indicated that this problem exists at the volumes examined.

Only one potential problem is seen with regard to pedestrians and the RTOR maneuver. If no pedestrian is immediately present when a vehicle arrives which intends to perform a RTOR maneuver, the vehicle may pull across the crosswalk before stopping. If a pedestrian arrives before the vehicle completes his turn, the pedestrian must either wait for the vehicle to move or walk out of the crosswalk and around the vehicle. This situation, however, was not observed to occur in this study. As pedestrian volume increases, the probability of a pedestrian being present when a vehicle arrives increases and with a pedestrian present, a vehicle is much more likely to stop behind the crosswalk.

Gap Analysis

The term gap as used here does not have the connotative meaning normally used with regard to vehicular traffic. Here, a gap is an opening between two vehicles in the cross street traffic which is large enough to permit one vehicle to make a right turn into the cross street traffic. If the distance between two vehicles on the cross street is large enough to allow two vehicles to enter, two gaps were counted. In essence, the number of gaps for each opening were recorded as the number of possible vehicle entries. The number of gaps in the cross traffic was determined by observing the cross traffic and recording a gap when the observer saw a gap large enough for one vehicle to enter. If the gap proved to be large enough for more than one vehicle to enter, the appropriate number of gaps was recorded.

Since the intersections used in the study had various cycle lengths and various percentages of red time, it became necessary to calculate gaps in terms of hours of red time on the approach. To analyze the data, it was decided to relate the number of gaps to the appropriate volume on the cross street. Therefore, cross street volumes were calculated in terms of vehicles on the cross street per hour of red time on the approach.

To examine these data, the computed gaps per hour of red time were plotted against the computed volume on the cross street per hour of red time on the approach. To properly examine the data, they were divided into two groups. The first group was for cross streets with only one lane of traffic in each direction. The plot for the data from this group is illustrated in Figure 4. The line fitted to these plotted points was determined with the use of nonlinear regression. The equation for this line is:

$$\text{gaps} = 5286.99\ (\text{volume})^{-0.03} - 4051.08$$

The gaps used here are the number of gaps in the cross traffic per hour of red on the approach. The volume is the volume of traffic on the cross street per hour of red on the approach. An approximate R^2 value for this equation is is .92.

The remainder of the data is for cross streets with more than one lane of traffic. The plot for this data is illustrated in Figure 5. The line fitted to these plotted points was again determined with use of nonlinear regression. The equation for this line is:

$$\text{gaps} = 456.46 - 0.32\ (\text{volume})^{0.96}$$

The gaps are the number of gaps in the cross traffic per hour of red on the approach. The volume used here is the volume on the cross street per hour of red on the approach. An approximate R^2 value for this equation is .90.

As can be seen in Figures 4 and 5, the plotted points are somewhat scattered. This condition can probably be attributed to the data collection technique. Even with the scattered data points fairly high R^2 values were obtained. The larger R^2 values result from the technique used to compute them for the nonlinear regression and are considerably larger than the R^2 values found using linear regression.

The values shown by the fitted lines in Figures 4 and 5 are by no means absolute values, but rather an approximate value that can be expected at a given intersection based on the number of lanes of cross traffic, and the volume of through vehicles on the cross street. This number of gaps thus found would be the maximum number of vehicles which could perform the RTOR maneuver provided a continuous queue of right turning vehicles is available.

As was mentioned earlier, only one and two lanes of cross traffic in one direction were used in this study. However, some opportunities were available to observe more than two lanes of cross traffic. It was seen that a vehicle performing a RTOR maneuver generally required a gap available in both of the first two lanes of cross traffic. Drivers however, did not appear to require gaps in a third lane to perform a RTOR maneuver. For intersection approaches with more than two lanes of cross traffic, Figure 5 should reasonalby well approximate the relationship between the number of gaps per hour and the volume of traffic in the first two lanes of the cross street per hour of red time on the approach.

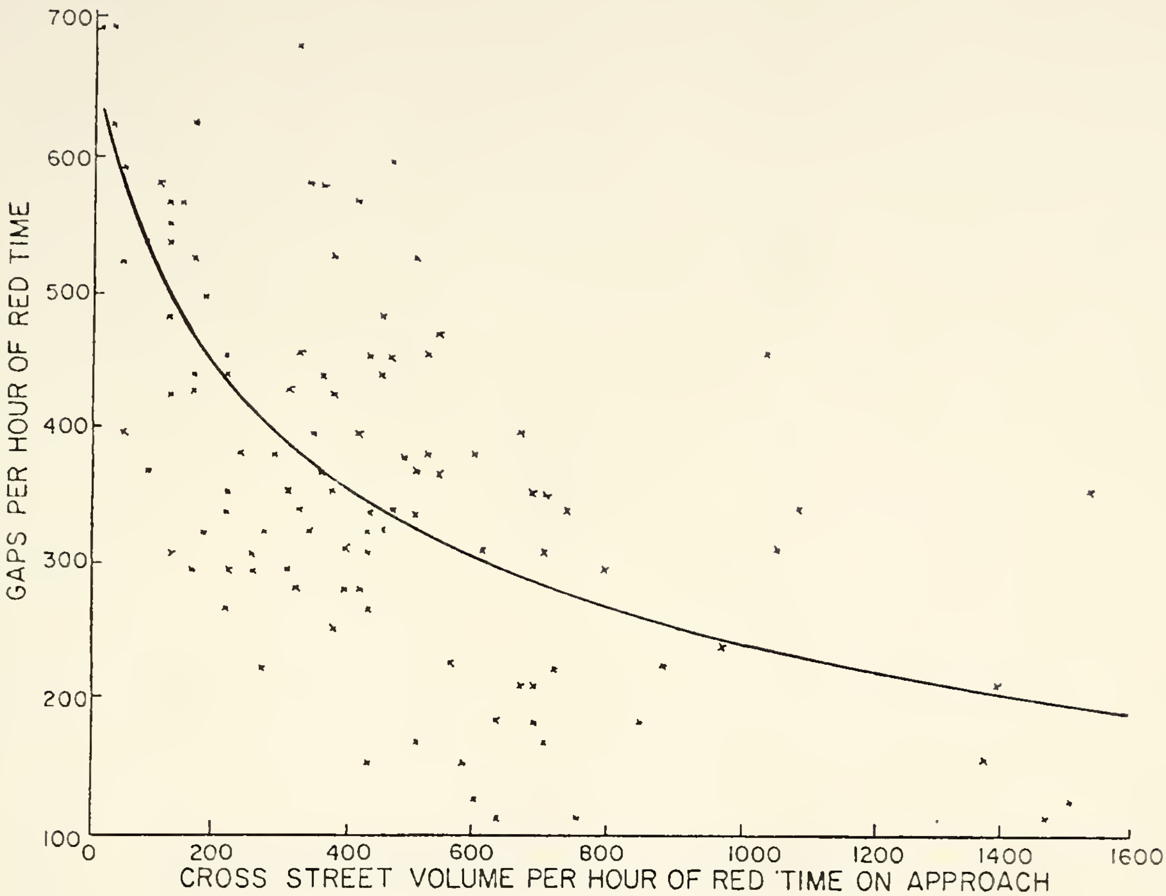

FIGURE 4. GAPS PER HOUR OF RED TIME VERSUS CROSS STREET VOLUME PER HOUR OF RED TIME ON THE APPROACH FOR ONE LANE OF CROSS TRAFFIC

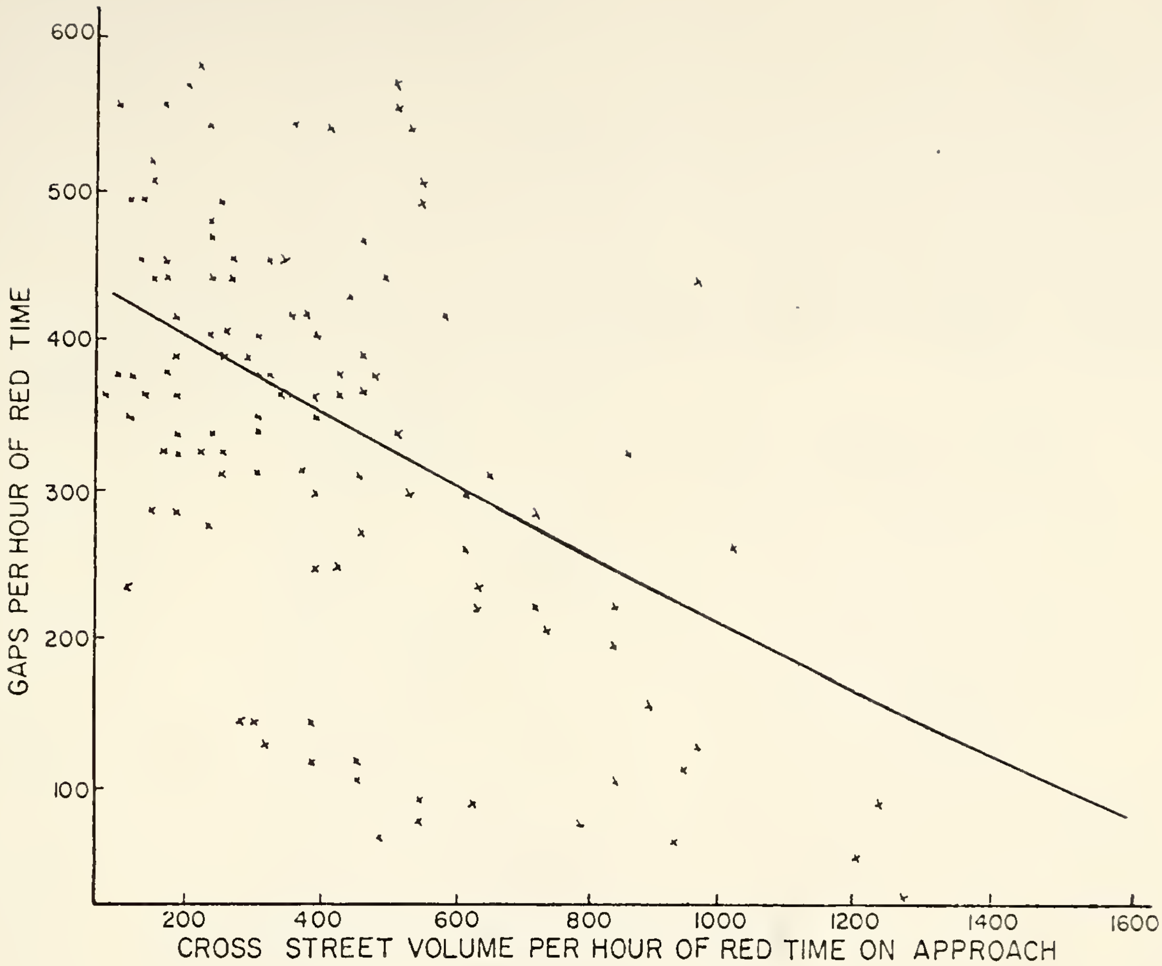

FIGURE 5. GAPS PER HOUR OF RED TIME VERSUS CROSS STREET VOLUME PER HOUR OF RED TIME ON THE APPROACH FOR MORE THAN ONE LANE OF CROSS TRAFFIC

FINDINGS

From the analysis of the data in this research project certain observations and findings were made. These observations and findings were:

1. A frequently stated concern about the RTOR maneuver is that the number of accidents will increase. It was found that at the intersections studied there was no increase in the total number of accidents. However, in the after period at the Indianapolis sites, a non-significant increase in total pedestrian accidents was noted. Collision diagrams prepared from the accident data indicated, however, that very few pedestrian accidents could have resulted from a RTOR maneuver.
2. Concern has also been expressed that pedestrians will be needlessly delayed or exposed to unnecessary accident hazards with the use of the RTOR maneuver. This study examined intersection approaches with pedestrian values up to 130 pedestrians per hour. No pedestrian was observed who had been placed in a more hazardous situation because of a RTOR maneuver during any of the data collection periods. Further, not a single example of pedestrian delay caused by a RTOR maneuver vehicle was observed. One potential problem between the RTOR maneuver and pedestrians, especially those approaching but not yet in the crosswalk, could result from

vehicles encroaching on the crosswalk. This problem, however, was not observed, perhaps because all approaches had adequate sight distances of the cross street from the normal stop position. Most of the few pedestrians observed who were delayed, all by right turn on green vehicles, hesitated in their crossing and thereby induced the motorist to continue his movement.

3. RTOR maneuver opportunities and actual use of these opportunities varied from intersection approach to intersection approach. Opportunities for RTOR maneuvers were utilized best when:
   a. A right-turn-only lane was available
   b. Cross street traffic speed was low
   c. Signal cycle length was short
   d. There was only one through lane on the cross street
   e. Sight distance of cross street traffic was long
   f. There were more than two phases in the signal cycle
   g. There were pedestrian signals present.
4. Delay reduction to right turning vehicles resulting from the RTOR maneuver was found. No occurrences of increased delay for right-turning vehicles was found. The amount of average delay reduction was found to vary from intersection approach to intersection approach, depending heavily on length of red time on the approach, and varied from almost zero reduction to as much as fifteen seconds per right turning vehicle that used the RTOR maneuver.

5. Very little driver irritation was found with the RTOR maneuver, even in locations where it had been recently implemented. The only form witnessed was an occasional horn-blowing by a stopped following vehicle. Such notice to the driver ahead almost never resulted in his utilization of RTOR maneuver.
6. The question of the availability of opportunities in the cross traffic for vehicles desiring to perform a RTOR maneuver was also examined. The number of opportunities for vehicles to enter the cross traffic per hour of red time on the approach was plotted against the volume of vehicles on the cross street per hour of red time on the approach. This procedure was followed for one lane of cross traffic and for more than one lane of cross traffic. Fitted lines to these plots can be used to approximate the maximum number of opportunities a RTOR maneuver could be performed from any approach knowing the cross street traffic volume and red time on the approach.
7. From previous studies on acceptance of gaps by right-turning vehicles made at Purdue University (7.36 seconds for median acceptability), it was found that the sight distances shown below should be available where the RTOR maneuver is permitted. To minimize blocking of the crosswalk, such distances should be available to a motorist when stopped at the stop line (or where it should be if there is none) if pedestrians are present.

Minimum Sight Distance

Speed in MPH	Sight Distance in Feet
20	217
25	271
30	325
35	379
40	434
45	488
50	542
55	596

8. On the basis of the findings of this study and experience indicated in the literature the following Warrants for Prohibiting the RTOR maneuver are suggested:
   a. The RTOR maneuver should be prohibited for safety reasons where:
      1. Sight distance of cross street traffic as shown in the above table is not available to the potential RTOR maneuver motorist at the stop line on his approach.
      2. A separate signal phase for a turning movement exists at the intersection which would conflict with a RTOR movement (the RTOR motorist may not be aware of this movement and hence not look for it).
      3. The intersection has more than four approaches (at such locations cross street traffic which conflicts with the RTOR maneuver may not be quickly identified by the RTOR motorist or the RTOR motorist may be able to turn into more than one street, thus creating unexpected conflicts).

b. The RTOR maneuver may be prohibited because of little benefit from the maneuver at locations where:

   1. There is very short red time for the approach.
   2. Cross street traffic is heavy for many hours of the signal-operating day (where the cross street is operating at capacity for many hours of the day).
   3. Pedestrian use of the crosswalk on the approach is heavy for many hours of the signal-operating day (at least one pedestrian is in the crosswalk during the red time for the RTOR motorist for many cycles during the day).
   4. Little right turn demand exists and there is no right-turn only lane available.

c. The RTOR maneuver may be prohibited because of possible adverse public reaction where:

   1. A school crossing route passes through the intersection.
   2. There are moderate to high pedestrian volumes.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Baker, William T., "Evaluating the Traffic Conflicts Technique", Federal Highway Administration, Washington, D. C.

2. Betz, Mathew J., Bauman, Richard D., Nader, Fareed, and Ellis, William, "Vehicle Headways at Street Intersections", Engineering Research Center, Arizona State University, Tempe, Arizona.

3. Box, Paul C., Traffic Control and Roadway Elements: Their Relationship to Highway Safety/Revised, Washington, D. C.: Highway Users for Safety and Mobility, 1970.

4. Cleveland, Donald E., ed., Manual of Traffic Engineering Studies, 3rd edition, Washington, D. C.: Institute of Traffic Engineers, 1964.

5. Cross, Seward, "Right Turn on Red Signal", Engineering Bulletin of Purdue University, Proceedings of the 54th Annual Road School, Lafayette, Indiana: Purdue University, Vol. LIII, No. 1, January, 1969.

6. Erion, Larry, "Right Turn on Red Signals", Traffic Engineering Department, St. Catherines, Ontario, Canada.

7. Federal Register, Highway Safety Program Standards, Docket No. 72-11, Traffic Laws and Regulations, Section 242.5 (d), Vol. 37, No. 150, August 3, 1972.

8. Graves, Paul B., "Right Turn on Red Signal", Traffic Engineering Department, Wichita, Kansas.

9. Hayward, John C., "Near Miss Determination Through Use of a Scale of Danger", Pennsylvania Transportation and Traffic Safety Center, The Pennsylvania State University.

10. Highway Research Board of the Division of Engineering and Industrial Research, National Academy of Sciences - National Research Council, Highway Research Board Special Report 87 - Highway Capacity Manual, Washington, D. C.: Highway Research Board, 1965.

11. Hochstein, Personal Correspondence to James E. Wilson, January 21, 1972.

12. Howard, H., "Analysis of Right Turn Accidents at Signalized Intersections", Traffic Engineering Department, Jacksonville, Florida.

13. Huffman, B. M., "Right Turns on Red Light", Traffic Engineering Department, Edmund, Alberta, Canada.

14. Indiana State Highway Commission, "Comments on Right Turn on Red Legislation", 1973.

15. Josey, J. L., "Should Right Turns on Red Lights be Legal? University of Missouri Study Seeks Answer", Highway Research Board, Highway Research News, No. 47, Spring 1972, p. 10.

16. Landen, J. C., Personal correspondence to Harold L. Michael, August 2, 1972.

17. Mathison, L. B., "The Controversial Dilemma of Right Turn on Red", Texas A & M University, 1972.

18. Matson, Smith and Hurd, Traffic Engineering, New York: McGraw-Hill Book Co., Inc., 1955.

19. May, Francis E., "Before and After Information on RTOR", Traffic Engineering Department, Fort Lauderdale, Florida.

20. National Joint Committee on Uniform Traffic Laws and Ordinances, Manual on Uniform Traffic Control Devices for Streets and Highways, Washington, D. C.: U.S. Government Printing Office, 1970.

21. National Joint Committee on Uniform Traffic Laws and Ordinances, Uniform Vehicle Code: Rules of the Road with Statutory Annotations, 1973, Annual Supplement, Charlottesville, Virginia: The Michie Company, 1972, Supp. 1973.

22. "New ITE Resolution", Traffic Engineering, Vol. 43, No. 3, 1972, p. 45.

23. Nolan, James, "Two Year Accident Summary", Traffic Engineering Department, Portland, Oregon.

24. Perkins, Stuart R., and Harris, Joseph I., Criteria for Traffic Conflict Characteristics at Signalized Intersections, Warren, Michigan: Research Laboratories, General Motors Corporation, 1967.

25. Petersmeyers, W. W., "Right Turns on Red Lights", Traffic Engineering Department, Regina, Saskatchewan, Canada.

26. Rankin, W. W., "Report on Results from Right Turn on Red Light Questionnaire Survey", Traffic Engineering, Vol. 26, No. 1, October 1955.

27. Ray, James C., The Effect of Right Turn on Red on Traffic Performance and Accidents at Signalized Intersections, Berkeley, California: The Institute of Transportation and Traffic Engineering, University of California, 1956.

28. Ray, James C., "Experiences with Right Turn on Red", Traffic Engineering, Vol. 28, No. 5, December, 1957.

29. Richter, Richard A., Personal correspondence to B. A. Cambel, March 16, 1972.

30. Scott, P. N., III, "Economic Benefits of Reduced Delay Due to Selected Control Procedures", A Civil Engineering 695 paper, University of Colorado, August, 1967.

31. Skiles, G. W., "Preliminary Summary of Three Years Accident Experience", Traffic Engineering Department, Jacksonville, Florida.

32. Smith, Donald L., "Right Turn on Red with Caution", Western ITE, December, 1967.

33. Solberg, Per, and Oppenlander, J. C., "Lag and Gap Acceptance at Stop-Controlled Intersections", Highway Research Record, No. 118, 1966.

34. "Some Right Turn on Red Facts", Department of Traffic Control, Oklahoma City, Oklahoma, November 19, 1971.

35. Tarpey, Michael P., "Officials Wary of Turn Law", Indianapolis Star, June 24, 1973.

36. Traffic Research and Surveillance Section, Office of Traffic Engineering, Minnesota Highway Department, Right Turn on Red Accident Study, Springfield, Virginia: National Technical Information Service, 1971.

37. Triffo, R. P., "Comments Concerning Right Turn on Red Signals", Traffic Engineering Department: Calgary, Alberta, Canada.

38. Van Gelder, William G., "Stop on Red Then Right Turn Permitted", Bureau of Highway Traffic, Yale University.

APPENDIX A

INDIANAPOLIS STUDY INTERSECTION APPROACHES

Table A-1. Indianapolis Study Intersection Approaches

Location	Approaches Studied
Bluff Road-Troy Avenue	Westbound
Delaware St.-St. Clair St.	Northbound
Emerson Avenue-16th St.	All approaches
Market St.-Alabama St.	Eastbound
Michigan St.-Alabama St.	Eastbound
Michigan St.-Blake St.	Eastbound, Westbound
North St.-Alabama St.	All approaches
North St.-New Jersey St.	Southbound
Pennsylvania St.-St. Joseph St.	Eastbound
Pennsylvania St.-29th St.	Eastbound
Pleasant Run Parkway-Meridian St.	Northbound
Raymond St.-Tibbs Avenue	Westbound
Ritter Avenue-16th St.	All approaches
Ritter Avenue-21st St.	Eastbound, Northbound
Sherman Dr.-21st St.	All approaches
Troy Avenue-Keystone Avenue	All approaches
Virginia Avenue-McCarty St.	Northbound, Westbound, Southbound

APPENDIX B

ACCIDENT EXPERIENCE AT RTOR INTERSECTIONS IN INDIANAPOLIS

Table B-1. Number of Accidents for Two Years Before and Two Years After Accidents by Type

Location	Before 1967	Before 1968	After 1969	After 1970
Alabama St.-Michigan St.	5-11-0	0-8-0	4-7-0	3-4-0
Alabama St.-St. Clair St.	1-3-0	5-4-0	1-5-0	2-3-0
Alabama St.-16th St.	4-12-0	3-18-0	3-12-0	4-10-0
Central Ave.-22nd St.	6-11-0	2-16-1	3-10-0	2-12-3
Cold Springs Rd.-38th St.	2-11-0	10-11-0	10-17-0	8-11-0
College Ave.-Fairfield Ave.	3-7-1	0-4-0	2-6-0	4-4-1
College Ave.-52nd St.	0-4-0	0-5-0	1-5-0	4-11-0
East St.-New York St.	4-17-0	7-5-0	2-1-0	3-2-0
East St.-Ohio St.	1-1-0	0-0-0	1-0-0	2-2-0
Emerson Ave.-English Ave.	4-12-0	3-4-0	6-10-1	3-4-0
Illinois St.-Indiana Ave.-Ohio St.	3-5-0	5-11-0	4-8-1	2-12-0
Meridian St.-Michigan St.	11-18-0	12-11-0	10-25-0	10-18-0
New Jersey St.-Ohio St.	1-5-0	1-2-0	3-0-0	3-2-0

00-00-00: Pedestrian Accidents - Property Damage Accidents - Personal Injury Accidents

00: Total Accidents

Table B-2. Number of Accidents for Two Years Before and Two Years After - Total Accidents

Location	Before 1967	Before 1968	After 1969	After 1970
Capitol Avenue-11th St.	10	7	1-5-0	3-4-0
East St.-McCarty St.	12	11	0-7-0	3-5-0
Franklin Road-Washington St.	22	29	3-5-0	4-5-0
Pleasant Run Parkway-Shelby St.	3-7-0	6	3-4-0	3-9-1

Note: When available accident information by type is displayed.

Table B-3. Number of Accidents for Two Years Before and Two Years After - Total Accidents, and Number of Accidents for One Year Before and One Year After - Accidents by Type

Location	Before 1967	Before 1968	After 1969	After 1970
Kessler Blvd.-Lafayette Rd.	13	7-7-0	2-5-0	3-6-1
Keystone Avenue-Prospect Avenue	18	2-8-0	2-5-0	1-9-0
New Jersey St.-New York St.	11	1-6-0	3-5-0	1-6-0

00 - 00 - 00 00

Pers. Inj. Acc. - Prop. Dam. Acc. - Ped. Acc. - Total Acc.

Table B-4. Number of Accidents for One Year Before and One Year After - Accidents by Type

Location	Before 1968	After 1969
Alabama Avenue-North St.	3-5-0	0-2-1
Brookville Road-Ritter Avenue	3-5-0	5-2-0
Central Avenue-Kessler Blvd.	0-2-0	1-3-0
Central Avenue-25th St.	3-5-0	6-6-0
Cold Springs Road-30th St.	4-2-0	3-3-0
East St.-Market St.	0-3-0	0-1-0
Franklin Road-38th St.	3-3-0	1-3-0
Georgetown Road-38th St.	8-7-0	5-15-0
Highland Avenue-New York St.	1-0-0	1-0-0
High School Road-34th St.	1-1-0	1-1-0
Martindale Avenue-25th St.	2-5-0	3-5-0
Michigan St.-Oriental St.	1-1-0	7-7-1
Morris St.-Shelby St.	4-13-1	7-7-0
Ritter Avenue-16th St.	3-5-0	5-4-0
Shelby St.-Southern Avenue	0-2-0	0-4-0
Shortridge Road-Washington St.	4-2-0	4-2-0
White River Parkway-30th St.	0-9-0	2-2-0

00 - 00 - 00   00

Key (printed vertically under each "00"): Per. Inj. Acc. - Prop. Dam. Acc. - Ped. Acc.   Total Acc.

Table B-5. Number of Accidents for One Year Before and One Year After - Total Accidents

Location	Before 1968	After 1969
Bluff Road-Troy Avenue	7	0-5-0
College Avenue-Ohio St.	3	1-5-0
College Avenue-11th St.	5	1-0-0
College Avenue-42nd St.	5	2-5-0
College Avenue-49th St.	7	2-3-0
Delaware St.-Ft. Wayne Avenue	6	3-3-0
Delaware St.-St. Clair St.	6	1-7-0
Delaware St.-25th St.	6	13
East St.-Morris St.	6	2-3-0
Illinois St.-South St.	9	0-2-0
Moeller Road-38th St.	11	1-4-0
New York St.-State St.	5	4-2-0
Pennsylvania St.-St. Clair St.	5	1-1-0
Pennsylvania St.-St. Joseph St.	2	0-2-0
Senate Avenue-South St.	1	0-1-0
Senate Avenue-11th St.	7	3-5-0
Washington Blvd.-29th St.	3	1-3-0

00 Pers. Inj. Acc. - 00 Prop. Dam. Acc. - 00 Ped. Acc.

00 Total Acc.